Accessible Transportation Technologies Research Initiative (ATTRI): State of the Practice Scan

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i. Abstract

The Accessible Transportation Technologies Research Initiative (ATTRI) focuses on research to improve the independent mobility of travelers with disabilities through the use of ITS and other advanced technologies. This report is one of three intended to provide an overview of technologies, innovations, and research that are applicable to the ATTRI vision. The particular focus of this report is on a State of the Practice Scan [SOP], to survey technologies that are currently in use on a wide scale within the United States. This document also contains characterizations of the challenges that face the stakeholders. Descriptions of user experiences with SOP technologies are determined by broad surveys of the user population.

The overall organization of this report echoes the organization of the overall ATTRI effort. ATTRI focuses on five technology areas to improve transportation for persons of its three stakeholder groups – people with disabilities, veterans with disabilities, and older adults: (1) Wayfinding and Navigation, (2) ITS and Assistive Technologies, (3) Automation and Robotics, (4) Data Integration, and (5) Enhanced Human Service Transportation. Review of each of the five technology areas considers the applicability of such technologies to four transportation modalities that ATTRI stakeholders encounter: (1) Transit, (2) Personal Vehicles, (3) First / Last Mile, and (4) Pedestrian. Where necessary, a cross-cutting modality category is also included.

Keywords: Accessible transportation, technology, community travel, international scan, best practices

II. Acknowledgements

The Department of Transportation has launched a new research program, Accessible Transportation Technologies Research Initiative (ATTRI), with plans for three major phases towards field testing new technologies in support of accessible transportation. This effort is led out of the Federal Highway Administration (FHWA), which entered into an Interagency Agreement (IAA number ED-OSE-14-K-0005) with the National Institute on Disability, Independent Living, and Rehabilitation Research (NIDILRR) to conduct ATTRI Phase 1 activities through the NIDILRR-sponsored Rehabilitation Engineering Research Center on Physical Access and Transportation, which is publically known as the RERC on Accessible Public Transportation (RERC-APT).

The contents of this report were developed under a grant from the National Institute on Disability, Independent Living, and Rehabilitation Research (NIDILRR grant number 90RE5011-01-00). NIDILRR is a Center within the Administration for Community Living (ACL), Department of Health and Human Services (HHS). The contents of this report do not necessarily represent the policy of NIDILRR, ACL, HHS, and you should not assume endorsement by the Federal Government.

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1 Executive Summary

The Accessible Transportation Technologies Research Initiative (ATTRI) focuses on research to improve the independent mobility of travelers with disabilities through the use of Intelligent Transportation Systems (ITS) and other advanced technologies. This report is one of three intended to provide an overview of technologies, innovations, and research that are applicable to the ATTRI vision. The particular focus of this report is on a State of the Practice Scan [SOP], to survey technologies that are currently in use on a wide scale within the United States. This document also contains characterizations of the challenges that face the stakeholders. Descriptions of user experiences with SOP technologies are determined by broad surveys of the user population.

The overall organization of this report mirrors the overall organization of the ATTRI effort. ATTRI focuses on five technology areas to improve transportation for persons of its three identified stakeholder groups – people with disabilities, veterans with disabilities, and older adults:

- Wayfinding and Navigation
- ITS and Assistive Technologies
- Automation and Robotics
- Data Integration
- Enhanced Human Service Transportation

Personal mobility has significant and profound impacts on employment, independence, social inclusion, entertainment and full participation in one's general community and society. Therefore, review of each of the five technology areas considers the applicability of such technologies to four transportation modalities that ATTRI stakeholders encounter:

- Transit
- Personal Vehicles
- First / Last Mile
- Pedestrian

Where appropriate, a cross-cutting modality category is also included. The above modalities focus on community travel: content relevant to intercity travel is included only when it is relevant to community travel. For example, technologies that address wayfinding and navigation within airport terminals may also be relevant for indoor transit stations, hence they are considered in these reports.

A summary of promising technologies and technology gaps is presented below. Specific products are not identified in the summary below, nor are we explicitly endorsing products mentioned in the body of this report. It is more important to focus on features and functions since these are what directly address ATTRI stakeholder needs, which is the intent of this effort.

Wayfinding and Navigation

Promising technologies

- Smartphone apps and websites for transit and pedestrian travel planning are common and readily available.
- In-vehicle navigation systems, websites, and smartphone apps are common and readily available for those who drive personal vehicles.
- Stop and train platform announcements presented in parallel over speakers and as text on screens serve a wide range of users and help with perceptual and cognitive disabilities.
- Pedestrian-only cycles on signal lights are especially helpful for intersections with complex layouts and high volumes.

Technology gaps

- Methods for incorporating user capabilities during transit and pedestrian trip planning are rare.
- Reliable and scalable localization that works underground or in GPS-denied regions is not widely available. Good localization is a requirement for navigation assistance.
- In-vehicle navigation systems often lack route preference settings that meet the needs of ATTRI stakeholders.
- Technologies are needed for addressing guidance during first / last mile traversal.
- Safe traversal of roundabouts remains a challenge.

ITS and Assistive Technologies

Promising technologies

- Real-time transit information helps reduce uncertainty and wait times.
- Automated gap plates on light rail and subways assist the boarding process.
- Wheelchair securement and crash safety standards have been developed and adopted.
- Some in-vehicle displays offer a 360-degree plan-view of the area surrounding personal vehicles for better situation awareness.
- Power assist and power wheelchairs can reduce fatigue during the first / last mile and longer pedestrian routes.

- Bike share systems and bicycle storage on transit vehicles may have value for ATTRI stakeholders who have the capability to safety ride a bicycle.
- There are several GPS-based navigation options for pedestrians who are blind or low vision.

Technology gaps

- Better methods for managing large grade changes when boarding transit vehicles are needed.
- Many personal vehicles are still difficult to enter and exit by people who are older or have a disability.
- Vehicle modification is still very expensive.
- Technologies that support last / first mile and pedestrian travel by people with cognitive disabilities are needed.

Automation and Robotics

Promising technologies

- Technologies for precision docking can make boarding and alighting easier.
- Rail platform doors can help prevent travelers from falling onto tracks or being struck by trains.
- Personal vehicles are becoming increasingly automated and intelligent, which potentially lowers effort and difficulty for certain users.

Technology gaps

- There is a gap in autonomous vehicles for the first / last mile. Most personal devices for this domain are not autonomous.
- Some shared-use mobility devices are over-used by people without disabilities, thereby limiting access to those who need the devices.

Data Integration

Promising technologies

- The number of relevant data sources is rising due to increased open data releases by public agencies. Successes include the rapid growth in transit apps due to the public release of schedule and real-time data by transit agencies.
- Crowdsourcing can be an effective method for filling information gaps, if implemented properly.

- Parking information and meter payment apps can help those with mobility and dexterity disabilities.
- Web-based map tools are helpful for scouting accessible routes and building entrance features.
- Bluetooth beacons can help provide low-cost localization inside buildings.

Technology gaps

- Some service providers do not release open data for use by third parties (e.g., some transit agencies). In some cases, the data is only partially released thereby limiting value and impact.
- Many data sources are stored in disparate locations and are hard to integrate into traveler information systems. Data quality, access rights, and use policies can vary considerably.
- Methods for acquiring and presenting data specific to the needs of ATTRI stakeholders are rare or lacking. Similarly, many mainstream traveler information apps are not accessible.
- Key data, like municipal infrastructure details, is either missing or stored in ways that make use by computer systems difficult.
- There is room for improvement on intelligent signal preemption and pedestrian crossing timing.

Enhanced Human Service Transportation

Promising technologies

- End-to-end multimodal trip planning has been deployed in some regions. Some systems support interregional trip planning.
- “One call” information centers support discovery of services and technologies.
- Integrated payment systems reduce confusion for people with cognitive or visual disabilities. Some smartcards can also be used for retail purchases.
- Flex-route transit has promise for reducing paratransit demand and improving travel by ATTRI stakeholders.
- Technology enhancements to fixed-route transit may relieve some of the demand.
- Dynamic scheduling, decision support, and dynamic monitoring have the potential to improve paratransit efficiency and service delivery.
- Transportation network companies (TNCs) offer increased transportation options to many ATTRI stakeholders. Some systems have specific features of direct benefit to those with certain disabilities. Likewise, cashless payment has high ease of use.

- Coordinated ride sharing for older adults has been successful in various parts of the country, including rural and suburban regions.
- Improved pedestrian infrastructure near bus stops by local municipalities can positively impact accessibility and use of fixed-route transit.

Technology gaps

- Many 511 options do not support the needs of ATTRI stakeholders as part of their mainstream services.
- Methods for service personalization based on end user needs are rare.
- Paratransit remains problematic for many reasons. Current implementations prohibit spontaneous travel, have poor scheduling, and are very expensive.
- Not enough taxi or TNC vehicles are wheelchair accessible.
- Some TNC drivers discriminate against people with disabilities even though TNC policies prohibit such behavior.
- It can be difficult to gather and maintain GIS data for pedestrian routes.

Readers interested in learning about innovations and research activities are referred to the companion Innovation Scan [INNO] and Assessment of Relevant Research Scan [ARR], respectively.

2 Introduction

2.1 ATTRI Vision

The Accessible Transportation Technologies Research Initiative (ATTRI) is a joint U.S. Department of Transportation (USDOT) initiative, co-led by the Federal Highway Administration (FHWA) and Federal Transit Administration (FTA), with support from the Intelligent Transportation Systems (ITS) Joint Program Office (JPO) and other Federal partners. ATTRI conducts research to improve the mobility of travelers with disabilities through the use of ITS and other advanced technologies. ATTRI leads the research, development, and implementation of transformative technologies, solutions, applications, or systems for people of all abilities to effectively plan their personal and independent travel. ATTRI will enhance the capability of travelers to reliably and safely execute independent travel. ATTRI will identify, develop, and deploy new transformative technologies, applications or systems, along with supporting policies and institutional guidance, to address mobility challenges of all travelers, in particular, travelers with disabilities.

ATTRI research focuses on the needs of three stakeholder groups: people with disabilities, veterans with disabilities, and older adults. ATTRI leverages recent advances in vehicle, infrastructure, and pedestrian-based technologies, as well as accessible data, mobile computing, robotics, artificial intelligence, object detection, and navigation. The technology is enabled by wireless communications that connect travelers and their mobile devices; vehicles; and infrastructure. The technologies used by ATTRI provide almost ubiquitous access to a wealth of real-time situational data sources, including data specific to transportation, municipalities, points of interest, crowd-sourced information, and accessibility data. Five (5) technology areas have emerged as ATTRI focus areas: *wayfinding and navigation*, *assistive technologies*, *automation and robotics*, *data integration*, and *enhanced human service transportation*.

2.2 Focus of this Document

The intent of this report is to provide a scan, across the U.S. and worldwide, of existing technologies in accessible transportation. Also included are those technologies which could be feasibly transferred to the transport sector that are applicable to the ATTRI vision.

As a means of focusing the scope of this effort, the main technology area headings are: *Wayfinding and Navigation*, *ITS and Assistive Technologies*, *Automation and Robotics*, *Data Integration*, and *Enhanced Human Service Transportation*. Personal mobility has significant and profound impacts on employment, independence, social inclusion, entertainment and full participation in one's general community and society. By focusing on personal mobility, this technology scan does not emphasize intercity travel. Some content is applicable to both types of travel, however, and examples from intercity travel may be explicitly identified as having value within community travel.

Another emphasis of this document will be on travel in modes other than personal vehicles. This is due to the high percentage of non-drivers in the ATTRI target populations. Travel modes of specific interest in this document will be pedestrian travel in the first / last mile, intersections, on-demand vehicles, and all modes of public transit. Terminals such as bus stops, airports, metro stations, etc., will also be considered.

This effort will include documentation of short-, mid-, and long-term implementation issues, lessons, technologies, and other factors that have been identified during the course of both federally-funded and non-federal deployments and research. These will be linked to the mission of ATTRI and accessible travel modes.

2.3 Target Users

Transportation plays a critical role in enhancing access to education, jobs, healthcare, recreation, leisure, and other activities. ATTRI research is targeted toward addressing the needs of the three stakeholder groups described below. Throughout the documents, they are also referred to as users or (ATTRI) stakeholders.

2.3.1 People with Disabilities

In 2012, the U.S. Census found that there were 56.7 million people in the United States with some form of disability, representing 18.7 percent of the U.S. population (Brault, 2012). In 2013, only 17.6 percent of persons with a disability, or one in six, were employed, the U.S. Bureau of Labor Statistics reports (BLS, 2014). In contrast, the employment-population ratio for those without a disability was 64 percent. Lower employment has a direct impact on economic well-being; people with disabilities have half of the household income of people without disabilities and are three times more likely to be living in poverty.

2.3.2 Veterans with Disabilities

Of the 2.3 million active-duty military personnel and reservists who had deployed to combat operations in Iraq and Afghanistan by the end of March 2011, 1.3 million have become eligible for Veterans' Administration health care services. Of those 1.3 million people, almost 685,000 (52 percent) have sought medical care from VHA since 2002. Through March 2011, the most common medical conditions diagnosed among the veterans of those wars who had ever used the VA's health care services were musculoskeletal disorders, which affect muscles, nerves, tendons, ligaments, joints, cartilage, or spinal disks (55 percent of such veterans) (Golding, 2011). In 2012, the percentage of working-age civilian veterans with a VA determined Service-Connected Disability was 20.2 percent (Erikson, et al 2014). Since some veterans acquire their disabilities as older adults, many are not familiar with using transit or paratransit services as part of daily life. Moreover, 40 percent of veterans reside in rural areas, where public transportation services are less available (Burkhardt, et al 2011).

2.3.3 Older Adults

There are 40.3 million people age 65 or older living in the U.S. according to the 2010 U.S. Census (Werner, 2011). Of those living outside nursing homes, 19.2 million, or roughly 50 percent, reported some kind of disability, and the incidence of disability increases dramatically as the population ages (Brault, 2012). With the aging of the Baby Boomer generation, the number of people age 65 or older is expected to grow to 88.5 million by the year 2050 (Census, 2012). A majority of those 50 years and older intend to live independently in their homes and communities, a recent American Association of Retired Persons (AARP) study found (Harrell, et al 2014).

2.4 Three Technology Scans

This document is one of three technology scans. Each scan considers the same five ATTRI technology areas (see section 2.5, below) that have a significant impact on a stakeholder’s ability to utilize transportation systems. These three scans are:

State of the Practice Scan [SOP], a survey of technologies that are currently in use on a wide scale within the United States. This document also contains characterizations of the challenges that face stakeholders. Descriptions of user experiences with SOP technologies are determined by broad surveys of the user populations.

Innovation Scan [INNO], a survey of technologies that have been recently introduced to public use and are being evaluated for effectiveness in select test markets prior to deployment at larger scales. User experiences with INNO technologies either represent a segment of the test market user population or are based on reports by the organization that is introducing the technology.

Assessment of Relevant Research Scan [ARR], reports on research technologies – both within and outside of the transportation domain – that have been assessed as showing promise to address the challenges that face ATTRI stakeholders. While ARR technologies are discussed with a vision toward their application to ATTRI stakeholder transportation needs, they represent little or no direct user experiences with such technologies in the transportation context.

When the same technologies are discussed across multiple scans, only the perspective of relevance to that scan will be presented. For example, autonomously driven people movers are discussed in both the ***Innovation Scan*** and the ***Assessment of Relevant***

Research. Within the ***Innovation Scan***, the details of pilot studies and deployments are described. Within the context of the ***Assessment of Relevant Research***, broader issues of presently under-addressed research, and considerations of what is necessary to make the technology applicable and accessible to ATTRI stakeholders, are discussed.

Technologies, and technology gaps, are viewed through the lens of **four functional areas: Vision, Hearing, Cognitive, and Mobility**. In many cases, a technology has value to more than one of the three target user populations. Therefore, it is helpful to consider how a particular technology helps with a function, rather than a population label. For example, a platform loading train with no step directly impacts people susceptible to mobility barriers, whether they are disabled, an older adult, or a veteran. Therefore, discussion of technologies in these documents centers on these functional areas unless there are nuances specific to a population (e.g., transportation service limited to a population for policy reasons).

These technology description and assessment scans focus on how technologies in each of the five ATTRI technology areas are being used or show promise at addressing the needs of ATTRI stakeholders and improving their access to, and use of, transportation systems within the United States. Material for these scans was derived from articles in the media, industry white papers, institutional surveys and reports, as well as from peer reviewed academic publication venues. Effort was made to collect and survey material from outside the U.S., as well.

These documents are not meant to identify unaddressed stakeholder needs and gaps. While unaddressed stakeholder needs and gaps in transportation services may be inferred from these scans, such inferences should be limited to the contexts of the primary information sources from which the scan material was drawn. Readers who are interested in transportation gaps and unaddressed stakeholder needs are referred to the companion ATTRI program website: http://www.its.dot.gov/attri/.

2.5 Technology Research Areas

ATTRI focuses on five (5) technology areas to improve transportation for persons of its three stakeholder groups: *wayfinding and navigation*, *ITS and assistive technologies*, *automation and robotics*, *data integration*, and *enhanced human service transportation*. Each of the five technology areas considers the applicability of those technologies to four transportation challenge modes that ATTRI stakeholders face:

- **Transit** - challenges and technologies affecting the use or access to transit services,
- **Personal Vehicles** - challenges and technologies affecting the use of personal vehicles,

- **First / Last Mile** - challenges and technologies for bridging the gap between home and fixed-route or main-line transit services, as well as between the transit services and the final destination, and
- **Pedestrian** - challenges and technologies for “human-scale transit” that does not involve transportation services. The term, “human-scale transit,” refers to walking and to devices that assist with human-scale travel such as wheelchair, motor scooter, Segway, bicycle, etc.

Two of the technology areas, data integration and enhanced human service transportation, have challenges and technologies that are applicable to all four transportation challenge modes. These are placed under the section heading, *cross-cutting*.

The following is an overview of each of these technology areas, with descriptions that span the three document types.

2.5.1 Wayfinding and Navigation

Wayfinding is the determination of a route of travel whereas *navigation* refers to the means at the individual’s disposal, such as following a textured pavement or moving from one landmark to another, by which they can traverse that route. Processes that comprise wayfinding and navigation include: familiarization, localization and orientation, path planning, path traversal (locomotion), guidance, annotation, update and communication. This area consists of exploration and development of situational awareness and assistive navigation solutions that can provide obstacle avoidance and wayfinding capabilities in indoor and outdoor environments.

Technologies that can assist with wayfinding and navigation include: path planning, advanced warning of events by using Global Positioning Systems (GPS), geographic information systems (GIS), and ITS equipment and technologies. Potential applications can recognize and detect stationary objects (e.g., doors, elevators, stairs, crosswalks, and traffic lights), read and recognize important text and signage based on a user’s query, and detect, track, and represent moving objects and dynamic changes to a traveler’s environment (e.g., people, shopping carts, doors opening, and moving vehicles). Wearable sensors, such as cameras, three-dimensional orientation devices, and pedometers, may be used in conjunction with a display unit to provide auditory and tactile guidance.

2.5.2 ITS and Assistive Technologies

An *assistive technology* is a technology that facilitates the functional independence of a user in any one of the four transportation challenge modes. The broad range of wireless and sensor-based communications and information technologies employed in ITS (Intelligent Transportation Systems), combined with a number of other assistive technologies, can create new innovative accessible transportation solutions. Included in this technology area are the traditional accessible, assistive, and adaptive devices that currently help with daily living activities, as well as new nomadic or carry-on devices. Together, these technologies will help track the user's movements, infer map information, and discover key sensor signatures to create routes and provide information in different accessible communication formats: audible, tactile and haptic. The devices used may include new innovations from the "Internet of Things" (IoT) being applied to wearable technology such as wristbands, glasses, clothing or other foreseeable applications. These technologies will also integrate with vehicles, infrastructure, and pedestrians using Dedicated Short Range Communication (DSRC) or other connective communication technologies to provide vehicle to vehicle (V2V), vehicle to infrastructure (V2I), and vehicle to pedestrian (V2P) communications allowing for connectivity throughout a trip. This area will also explore other emerging technologies within the connected vehicles, connected automation, and connected cities initiatives under the USDOT's connected vehicle research program.

2.5.3 Automation and Robotics

Automated vehicles and robotics are expected to improve mobility for those unable or unwilling to drive and to enhance independent and spontaneous travel capabilities for travelers with disabilities. Machine vision, artificial intelligence, assistive robots (sometimes partially humanized), and facial recognition software can potentially solve a variety of travel related issues. Devices and terminals installed in vehicles to provide functionalities of virtual caregivers or concierge services, promise to guide travelers and assist their decision making. One area of particular interest is exploring the use of vehicle automation to solve first / last mile mobility issues and possibly providing connections for all travelers to existing public transportation or other transportation hubs. Applications in this area may also include collaborative robots that not only assist with activities in daily life such as walking, but also work with individual travelers and human transportation services to provide related concierge services at different stages of travel and hence improve personal mobility across the transportation network.

2.5.4 Data Integration

This technology area includes solutions that enable the integration of data and information systems to create new accessible transportation applications. At a minimum, it has two aspects: information that travelers with disabilities need, and information that travelers with disabilities can provide. Travelers with disabilities need in-depth accessibility information about points of interest (POIs), infrastructure, facility amenities, and potential obstacles, integrated with maps and other information for their intended route. Some of this information can be provided via crowdsourcing or at least by sharing in a way that is similar to social media fitness apps. Many times transportation and facility providers are unaware of the specific needs for travelers with disabilities. Data integration technologies can also provide a means by which travelers can document those needs, communicate them to the service providers, and thereby have them met. For example, a traveler can provide his or her specific information to build a user profile. Based on the user profile, applications can be developed to provide location based services, or to alert relevant authorities in advance of a user's trip requiring special accommodations, such as a wheelchair at the airport.

2.5.5 Enhanced Human Service Transportation

Human service transportation consists of mobility services for clients of a specific human or social service agency. The focus of the *enhanced human service transportation (EHST)* technology area is real-time, multimodal trip and services planning and traveler decision support applications that assist travelers with finding and choosing accessible transportation solutions that best meet their mobility needs. This may include pre-trip planning and information that integrates multimodal options into a complete origin to destination trip. Applications in this area could include an integrated payment system where travelers can use the same smart card or mobile app to pay for various types of transportation, mobility options, and parking. Other applications of interest might possibly link paratransit, demand-response transportation, and fixed-route transit in order to increase flexibility, optimize the use of assets and options of all travelers, especially those with disabilities.

2.6 Universal Design

The principles of *universal design* will be mentioned throughout this document. Universal design is a design philosophy that maximizes the applicability of a technical solution for one stakeholder's challenge to the challenges faced by other stakeholder groups (CUD, 2016). For example, the requirement that all sidewalks have corner curb cuts to permit accessibility by persons with mobility disabilities is also a solution for the challenges facing bicycle riders, persons with strollers and baby carriages, and persons using grocery carts and wagons.

3 State of the Practice Scan

This scan identifies current practices in accessible transportation, ITS and assistive technologies, applications and systems for travelers with disabilities, including veterans with disabilities, older adults, and people with disabilities. *Current practice* means that the technologies described are currently in public use on a large scale. The modes of transportation considered by this report are transit vehicles and systems, which may or may not be accessible. Contributing technologies are from fields such as telemedicine, rehabilitation, defense, and robotics. The report also documents lessons learned from the use and implementation of existing technologies and identifies implementation issues as well as technologies and methods used to address them.

It is important to note that ATTRI stakeholders often employ a variety of transportation modes. For example, one survey of people with various disabilities showed the top three modes were transport by a friend (24%), walk (22%), and take a bus (20%) (Jonnalagedda, et al. 2014). Other commonly-used transportation options included paratransit (14%), personal vehicle (11%), and taxi (9%).

In many sections of the document below, discussion is centered on user capability (e.g., mobility) rather than ATTRI stakeholder group (e.g., older adult). Many technologies have direct value to multiple stakeholder groups since they meet the needs of people with specific capability concerns. Specific stakeholder groups are discussed when group membership is tied to a particular point of discussion. For example, the Veterans Transportation and Community Living Initiative (VTCLI) is designed to meet the needs of veterans.

Other studies and surveys focus on current transportation needs and gaps identified by ATTRI stakeholders. Readers who are interested in generalized scenarios of such challenges are referred to documentation on the ATTRI Applications Workshop that was held May 18-19, 2015, in Washington, D.C.: http://www.its.dot.gov/attri/attri_appworkshop.htm.

3.1 Wayfinding and Navigation

This section is organized as follows. Section 3.1.1 explains the terms that were briefly introduced in section 2.5.1, above. Sections 3.1.2 – 3.1.5 describe the state of the practice in wayfinding and navigation for each of the four transportation challenge modes.

3.1.1 Process Descriptions

The identification and naming of the below processes is based on material found in several research papers (Montello and Sas, 2007; Strumillo, 2010; and Jonnalagedda, et al., 2014). These are described here to provide clarity and common terminology when discussing how technologies support transportation.

3.1.1.1 Familiarization

Familiarization is the process by which an individual forms a mental map of key features of the terrain that they will be crossing, typically before they commit to traveling in that area. This is for the purposes of trip and path planning, noting reliable landmarks, knowing when to change a mode of transport, and knowing when to take an action. For example, people with visual impairments may make note of indoor/outdoor distinctions, terrain textures, sounds typical of an area, the bearing they should keep as they walk through a station, and other non-visual landmarks. Travelers with mobility impairments need to be aware of stairs, the functioning status of elevators, whether or not the vehicles in service along a transit line permit them to enter and secure themselves in the vehicle, and the type of securement features. Familiarization of persons with cognitive or hearing disabilities may involve choosing a mode of transportation that has reliable visual signs that announce the stops, or knowing the visual landmarks along a bus route that are unmistakable for the user to know when to get off the vehicle. For all ATTRI stakeholders, familiarization information can also include knowing the schedules of fixed route transit vehicles, knowing the location of the transit stops, being able to find them, the capacity and layout of the vehicle seating, and the likelihood of finding a seat during diverse periods of the day.

3.1.1.2 Localization and Orientation

Localization is the ability of a person to know where they are along their planned trip path. It can involve knowing the identity of the transit station, where they are inside of the station, the name of the street their bus is on, and the names of the cross streets they are near. It may also involve the location of elevators, where to enter or to exit a transit station, or where to transfer from one line or direction of travel to another. It can also involve knowing the direction and time of travel to amenities, such as a newsstand, cafe or rest room.

Orientation is the direction and bearing of the traveler with respect to key pathways and landmarks within a transit station, within a vehicle, or on the streets after exiting a vehicle or transit station, and is the means by which anyone determines their direction of subsequent travel. While everyone can suffer disorientation in transit, orientation often presents challenges to the independence of users who might have difficulties recognizing landmarks from a distance or in situations with lots of movement, noise and activity.

3.1.1.3 Path Planning

Path planning is the actual planning of the route that a person will take from origin to destination(s) and the return trip, and involve multiple modes of transit as well as multiple destinations. Successful path planning requires good familiarization and the user or caregiver feeling confident in their ability to localize and orient the traveler along their path. Map websites may be helpful for some trips.

3.1.1.4 Path Traversal

Path traversal refers to the actual execution of the path plan. Sometimes it is referred to as *locomotion*. One aspect of this process is following the correct travel plan. Another aspect of this process is recovery from interruptions and unexpected departures from the original travel plan. During traversal, anything can result in a departure from a plan, so a person's abilities to detect, recover from, and resume travel from such departures are essential. For example, if a vehicle breaks down and makes an unexpected stop at a location other than the destination, would the traveler have enough information at their disposal to be able to localize and orient themselves, plan alternative paths and resume travel?

3.1.1.5 Guidance

Guidance is the ability of a traveler who is unfamiliar with their path to destination, to traverse it. Guidance aids can be: someone who accompanies the traveler, a white cane, guide dog, transit personnel in stations and on the vehicles, or even fellow travelers and passers-by. Guidance aids can also be smartphone applications with interfaces that are appropriate for the user's disability.

3.1.1.6 Annotation

Whatever map a traveler uses, whether it is physical, electronic or mental, there is sometimes the need to make *annotations* to personalize it for the user or for the particular trip. For example, a map might show one exit in schematic form, but when traversing the area that the map should describe, there are multiple portals that could be described as exits. An annotation can serve to help the user determine which portal corresponds to the exit they desire.

3.1.1.7 Update

There are two types of updates that are of concern to wayfinding and navigation. The first refers to updates that are motivated by dynamism in the environment: a schedule change, a route being temporarily out of service, a temporary obstacle to navigation, or an elevator taken out of service for repair. The second type of update is that of personal preferences and priorities of the traveler.

3.1.1.8 Communication

Any knowledge that is useful for an individual user's familiarization, planning and traversal choices can be communicated to somebody or something, be it another traveler, a caretaker, an assistant or guide, or to a technology. Hence, that knowledge needs to be documented somehow and transferable in a data interchange format. Any documented knowledge will also need to be updated, and those updates communicated, as well. Any traveler will encounter difficulties if transit schedule and route changes are not communicated or are communicated via a channel to which the traveler does not have access.

3.1.2 Transit

Two articles provide a helpful understanding of wayfinding and navigation needs when older adults, persons with disabilities, and veterans with disabilities use transit services. First, Montello and Sas (2006) provide an overview of the human factors of wayfinding and navigation, indifferent of a person's abilities and applicable to all users of transit systems. Second, Thatcher, et al. (2013) focuses on persons with disabilities and an aging population whose vision, hearing, and/or mobility are declining. Literature specific to this section's topic was not found that identifies the transit technology needs of veterans with disabilities but these needs are expected to be in close alignment with other stakeholder groups. Material that addressed specific needs emphasized those who are blind, visually impaired, or have a cognitive disability.

Technology for wayfinding and navigation within transit systems concentrates mostly on the processes of: familiarization, localization, orientation and guidance during traversal.

Familiarization technologies primarily focus on allowing users to build a mental map (cognitive map) so that localization and orientation will be easier, quicker and safer. Current familiarization technologies for transit fall into two categories: technologies that are specifically tailored for ATTRI stakeholders and those which are not. In the case of technologies that do not target ATTRI stakeholders, familiarization is mostly for path planning, available seating capacity, and visual orientation within a transit terminal, such as indicating departure gates. Such technologies exist as smartphone applications and on web sites: typically those of the transit agencies, themselves (e.g. 511.org). Most technologies presuppose a sighted user; sometimes they are designed with a screen reader in mind; they often do not include information that ATTRI stakeholders would find useful for their particular needs or preferences.

For persons with visual disabilities, the technological state of practice spans the four processes mentioned above. These are the “traditional technologies” of: guide dogs, special training by O&M (orientation and mobility, sometimes called “Travel Training”) experts, using tactile maps (e.g., Espinosa, et al 1998; Subrayan, 2009), or relying on the help of sighted assistance. This state of practice can be improved, for example, by being more affordable, less labor intensive, more available or by providing more coverage and descriptions of what a person must traverse.

Detail on the challenges facing persons with visual disabilities is also provided in the literature (Saurburger, 2013; Strumillo, 2010; and Liu, et al., 2007). Saurburger (2013) discusses traditional technologies for familiarization and localization involving aids to building mental maps, which are either through guided exposure to the environment, through auditory instructions, or through the use of tactile maps. Strumillo (2010) discusses the problem of outdoor mobility for the visually impaired. Special attention is given to the information the blind traveller needs in order to be safer and more skillful in mobility.

Livingstone-Lee, et al. (2014) identifies the wayfinding and navigation needs of persons with cognitive disabilities when using transit systems. Such needs are: wayfinding and navigation via landmark based familiarization and localization, a means of organizing and recalling the landmarks, a means by which trusted caregivers can know where the person is and to intervene if they deviate from the prescribed route, aids or tools to help the transit rider be redirected back on their correct path, and single payment systems for transit involving multiple modes or that traverses multiple regions.

For the current state of the practice, a major limitation for most systems is reliable and scalable localization and navigation technology that will work in underground locations (e.g., transit stations). This is a recurring challenge for technology developers.

3.1.3 Personal Vehicles

Little information was found that describes the state of the practice in wayfinding and navigation for use in personal vehicles by ATTRI stakeholders. From the authors' own personal observations and experiences, the only technology that is diffuse and on the market are in-vehicle navigation systems. Such systems have significant potential to support older adults and some persons with cognitive disabilities due to reduced cognitive load and context-dependent wayfinding guidance. These navigation aids often consist of speech-based interfaces to GPSs and large format maps with indications of landmarks that a person can use to survey terrain and preferred routes before departing. Gaps exist, however, in the quality, accessibility and extensiveness of the data. For example, while landmarks might be provided for a 2-D map, road surface, speed bump, and terrain type data might be missing. There is anecdotal evidence that driver rehabilitation therapists can train clients with these systems to support safer, independent driving of modified vehicles with low clearances. Likewise, most in-vehicle navigation systems do not support capability-based routing (e.g., avoiding unguarded left turns).

3.1.4 First / Last Mile[1]

Presently, the most common technological solutions to first / last mile transit are: commuter parking lots adjacent to transit stations or car pool areas, bicycling and walking. None of these are particularly suited to increasing the frequency, scope or safety of first / last mile travel by ATTRI stakeholders. Further, while flexible transit solutions have been proposed, the projects

[1] Some material for this section is derived from the ATTRI Stakeholder Engagement: User Needs Assessment Workshop held in April 2015, and the ATTRI Applications Workshop held in May 2015.

are uncommon due to the difficulties of guaranteeing on-call service to large areas with sparse feeder patterns and to the unpredictability of traffic congestion.

Of specific interest to wayfinding and navigating in the first / last mile, challenges faced when navigating unfamiliar environments were identified mostly for travelers with visual mobility disabilities. Both groups face challenges of finding an accessible route that is suited to their personal level of ability. As can be expected, the discovery of such a route must be done before travel. Yet, there is also the need to find such routes in the rare, emergency situations, as well, particularly if the local area changes as a result of the emergency.

Travelers with mobility and visual disabities also diverge in their needs, as well. For travelers with visual disabilities, challenges in the first mile consist of unknown or unexpected modifications to their usual walking path of travel, such as obstacles and construction. Particularly for bus usage, the greatest difficulties are either in finding a between-intersection bus stop, or if the bus stop is in an intersection, identifying the correct bus to get on when multiple buses arrive. For example, buses may stack at an intersection due to the timing of the signal lights, leading to the second bus driver loading or unloading a full bus length from the stop. This can be confusing for people who are blind or low vision and prohibit safe boarding for those with mobility disabilities who need good bus docking to the curb (e.g., kneeling buses, ramps, etc.). For the last mile, getting to their destination from the transit stop is a challenge in wayfinding and navigating in unfamiliar environments.

Of the other ATTRI stakeholders, little is mentioned in the literature although some observations were raised in workshop discussions. Veterans with disabilities often live in communities that are distant from fixed route transit. Consequently, they face challenges related to accessing fixed route transit in the first place. Older adults tend to not use fixed route transit at all, so technologies that encourage them to use it might also address their needs for the first / last mile.

In summary, a large gap exists in wayfinding and navigation for the first / last mile for technologies that specifically address the needs of ATTRI stakeholders.

3.1.5 Pedestrian[2]

As for the previous section, the state of practice for pedestrian wayfinding and travel is that there do not seem to be many technologies that are readily available, diffuse, and of specific interest to ATTRI stakeholders. The challenges that pedestrians face are documented primarily for people with visual and mobility disabilities, and are distinguished between indoor and outdoor environments. Material in support of pedestrian wayfinding and navigation specifically for older adults and veterans with disabilities was not found.

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[2] Material for this section is drawn from Fallaha, et al. (2013), Montello and Sas (2007), Jonnalagedda, et al. (2014), the *ATTRI Stakeholder Engagement: User Needs Assessment Workshop* held in April of 2015, and the *ATTRI Applications Workshop* held in May of 2015.

Indoor challenges for travelers with mobility disabilities include transitional environments and indoor carpeting. A challenge for those with visually disabilities in indoor environments includes use of public facilities. Airports and large transportation facilities present a serious problem for wayfinding. Those with mobility and visual disabilities both found loud environments and unfamiliarity of their surroundings to be challenging in indoor environments. Audible announcements are also problematic for those who cannot hear, so screens with text versions of announcements are important. These are common in many airports and train stations.

Many travelers, especially those with disabilities, find the absence of sidewalks and unfamiliarity with their surroundings to be challenging. Intersection crossing can be problematic, particularly in busy urban areas, and can be critical for access to transit. Pedestrian only cycles are especially helpful for intersections with complex layouts and high volumes.

Locating the crosswalk is a major safety issue to people with visual disabilities. To remedy this challenge, some municipalities have deployed audible displays at signal lights so that people who are blind or low vision can localize their corner and more accurately orient themselves while crossing the street. Some audible displays require pedestrians to press an infrastructure button, which limits noise pollution for neighboring venues. Raised sidewalk markings are also frequently used to warn pedestrians they are about to enter an intersection. Mid-block street crossings are sometimes used near major transit hubs if the road grid is large. Occasionally, audible alerts are deployed in conjunction with roadway embedded LEDs that are designed to alert nearby drivers, thereby increasing safety for those who walk slowly or cannot see oncoming traffic. Traversal of roundabouts remains a major gap. Current technology approaches mostly center on grade separation, which is generally cost prohibitive in most cases.

No literature was found that discusses widely deployed pedestrian wayfinding and navigation technology designed specifically for older adults and for veterans with disabilities.

3.2 ITS and Assistive Technologies

An assistive technology is a technology that facilitates the functional independence of a user in any one of the four transportation challenge modes described above. It is worth noting that some transportation technologies have their roots in the assistive technology domain. For example, the Segway is a byproduct of the iBOT wheelchair. Therefore, some assistive technologies have the potential for wider value through alternate applications or extensions. Key assistive technologies that demonstrate this potential are described in the subsections that follow.

An Intelligent Transportation System (ITS) technology is one that has the possibility of integrating vehicles, infrastructure, and pedestrians into a communicative and collaborative information technology architecture for the purposes of improving travel safety and vehicular throughput, reducing fuel consumption, and reducing greenhouse gas emissions. In the near future, this integration may be enabled on a broad scale via Dedicated Short Range Communication (DSRC) or other communication technologies, to provide vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I), and vehicle-to-pedestrian (V2P) communications. Relevant ITS technologies have been deployed in smaller and more specialized SOP implementations, which are discussed in the subsections below.

Numerous assistive technologies and ITS solutions were described in a recent FHWA workshop report (Morton & Yousuf, 2011). Some methods identified at this workshop focused on low-tech approaches, largely in the form of changes in the built environment or decades-old technologies (e.g., dial in phone systems). While these are useful and effective, they are out of scope of the ATTRI research program and are not described in detail within this document. Also, some ITS technologies are described elsewhere in this report for organizational reasons (e.g., fare payment, transit information systems, etc).

3.2.1 Transit

For people with disabilities, there is much attention given to the wayfinding requirements of those with visual impairments, particularly in the context of a multimodal journey, which often involves public transportation of more than one form. A variety of issues, useful assistive technologies and other ITS solutions currently utilized alongside transit operations were identified during the aforementioned FHWA workshop (Morton and Yousuf, 2011).

Most solutions aligned to transit focus on two user populations: (1) people who are blind or low vision and (2) those who use wheelchairs or scooters. Examples of technologies for the former include many of the wayfinding technologies mentioned in earlier sections of this document and tactile surface markings which work to indicate paths of travel and train platform edges. The most common form of nascent ITS and assistive technology in transit is real-time information regarding vehicle arrival times and status, which are incorporated into databases that enable many people to plan their travel in a better way. As an assistive technology, this responds to the needs that are described in earlier sections, provided that there are acessible information and interfaces for the traveler to use. Unfortunately, many real-time information systems are only partially accessible, indicating a significant gap even in this promising technology area.

Assistive technologies in the transit modality for people who use wheelchairs are heavily skewed towards devices designed to mitigate physical barriers. These traditionally fall into grade change barriers, wheelchair parking and securement, and fare management. Some transit environments employ assistive technology in support of non-physical barriers. Better methods for managing large grade changes when boarding transit vehicles remains a large gap in the state of practice.

In an ideal transit environment, all grade changes are managed through universal design techniques, ramps, and well-maintained elevators and escalators. In reality, the age of transit stations, variability in rolling stock, and the physical environment at bus stops create instances where vehicle mounted lifts and ramps are necessary. In extreme cases, some train stations also employ platform based lifts to address significant elevation barriers. Many of these interventions require human service, like station agent or bus driver actions. In general, vehicle lifts have a bad reputation among riders and agent operated lifts at train stations are slow and inconvenient. While new lift technology has potential, architectural solutions and low floor vehicles with ramps are likely to be more efficient and well-received by the public. Unfortunately, there are still open research issues with ramp slope design (Steinfeld, et al 2010).

When the grade change or gap between a vehicle and the stop or platform is small, automated or rider activated gap plates are an option. For example, the Portland TriMet MAX Light Rail includes buttons at doors which activate gap plates and small ramps on demand. The wheelchair parking area of MAX cars illustrates the universal design of this solution because the same area can also be used for bikes and strollers.

Wheelchair and scooter securement approaches vary based on municipality and region of the world, but most transit systems in the United States still employ belt-style technology. The former Rehabilitation Engineering Research Center on Wheelchair Transportation Safety (RERCWTS, 2015) conducted significant research on device securement and found many problems with poor belt attachment decisions by transit operators. This led to a strong push for the RESNA WC18, WC19, and WC20 standards, which are designed to facilitate both better belt securement in daily practice but also better wheelchair design for improved crashworthiness. This has created an opportunity for better safety and experiences by people with disabilities while riding transit vehicles, but belt-oriented approaches are still generally undesirable due to high time costs and driver encroachment into the personal space of the rider.

Some agencies, especially in Europe, address device securement by having riders back up to a reinforced wall for a rear-facing ride. The wall absorbs device motion during any sudden stop and limits the risk of injury to the rider and bystanders. Such simpler, rear-facing methods are not popular within the United States, though. New systems with robotic arms are now on the market. The goal is to eliminate the need for belt securement, thus increasing speed and eliminating encroachment into personal space.

Assistive technology for fare management is often implemented as alternative fare gates in train stations which provide wider clearance for wheelchair and scooter users. Alternative fare gate designs typically utilize swinging door structures rather than the traditional turnstiles. Smartcard and NFC phone methods interact with these assistive technologies and are covered in a later section.

3.2.2 Personal Vehicles

One of the more challenging aspects of personal vehicle use by people with disabilities and those who are older is entry and egress. Advances in this area have occurred, but this remains a large gap. Vehicle modification with assistive technologies is a common approach but such technologies can be very expensive and often negatively impact a vehicle's resale value due to the custom nature of the changes. People who are older, especially those with physical limitations, can encounter significant difficulty managing vehicle doors due to space and design barriers (James, 1985; Steinfeld, et al 1999). Therefore, vehicles which are inherently easier to enter and exit are more desireable. Sliding doors, wide clearances, and the ability to easily swing legs through a door opening are critical vehicle design features.

Vehicle modification remains very expensive and cost-prohibitive for many personal vehicle users. Little progress in the market has been made at closing this technology gap with low cost solutions. Roosemalen, et al (2010) identified other assistive technologies such as driving controls, wheelchairs used as seats, and safety and information systems as areas where technology exists for more accessible driving by people with disabilities. Examples include drive-by-wire, which eliminates the need to operate a vehicle via physical movements of limbs, the convenient activation of secondary dashboard controls (e.g., heating), in-vehicle navigation, which could be enhanced via future ITS technologies, and advanced safety and control systems such as automatic lane keeping and adaptive cruise control. The latter are discussed in greater depth section 3.3.2.

The recent 360-degree vision systems that convert video from cameras into an integrated, plan-view display (Howard, 2014; Nissan, 2015; Valeo, 2015) also have potential value to those who need help maintaining good situational awareness when checking blind spots and car surroundings due to limited neck movement. IThese kinds of situation awareness displays may be perceived to be helpful by those with post-traumatic stress disorder. Confirmation or rejection of this possibility is needed.

3.2.3 First / Last Mile

Many of the assistive technologies developed for daily life also have direct value on travel within the first / last mile or during pedestrian travel. For example, power assist wheels for wheelchairs are a traditional technology which has an impact during travel. The small boost in wheel propulsion provided by these wheels can dramatically extend the realistic neighborhood travel distance and manageable sidewalk slopes for manual wheelchair users. Likewise, power wheelchairs and scooters are often preferred by people who normally use manual wheelchairs or canes when first / last mile distances are larger. These technologies extend the geographical footprint of the first / last mile, thus increasing transit options and flexibility.

In more controlled environments, moving walkways and covered pathways are very effective in reducing the effort and exposure to weather. Moving walkways are very common in large airports but are sometimes also seen in other large physical structures. Covered walkways decrease exposure to the sun, rain, and snow thereby mitigating the impact of inclement weather. While not high tech, both extend the traversabile distance for people who normally cannot walk moderate lengths or are susceptible to weather. Both have universal design value in that they benefit almost all populations.

Within U.S. cities such as Boston, Pittsburgh, San Francisco and Washington, DC, bicycles and bicycle sharing programs are becoming more ubiquitous, offer a first / last mile solution, and are one possible option for older adults and persons whose disabilities do not prohibit them from physically operating a bicycle. To encourage bicycle use, transit agencies began allowing them to be carried on light rail transit systems as many as 30 years ago (MBTA Boston, T in Pittsburgh). Unfortunately, whether or not the bicycles can board is often at the discretion of transit operators, who are sometimes arbitrary in their decisions and criteria. Anticipation of rider loads, which a bicyclist would not necessarily know, is often a reason for denying a bicyclist the privilege of boarding a vehicle with a bicycle. Some of the unpredictability has been reduced now that buses offer external bicycle racks that do not interfere with passenger comfort, but for other modes of transit, the unpredictability of being allowed to board is still a major inhibitor. It should be noted that in the Netherlands, where bicycles are the predominant mode of first / last mile transportation, intercity light rail trains have platforms on the same level as the train deck and large spaces reserved for bicycles on the trains. Caltrain also regularly has a bicycle car at the end of their trains.

Bicycle share systems are now becoming more ubiquitous in the U.S. This is a form of pay per use infrastructure in which a person rents a bicycle from one location and can then leave it at another location. Many times the services offer smartphone applications that allow one to locate the bicycle share stands, as well as the availability of drop-off space on stands. If there are no drop-off locations for bicycles at a particular stand, some bicycle shares have the policy that the bicycle should be taken to the next closest stand. Again, this option is limited to ATTRI stakeholders who have the capability to safety ride a bicycle.

First and last mile challenges for persons with cognitive disabilities are consistent with those of wayfinding and navigation. That is, such travelers could best be assisted by personal technologies that give them specific, step-by-step instructions, and in the event that they are disoriented, can allow caregivers or trusted by-standers to provide assistance. The best solution to this challenge is presently a human guide. Methods and technologies that leverage such infrastructure are lacking from helping persons with cognitive disabilities navigate the first / last mile.

3.2.4 Pedestrian

Sendero is a well known and established product for pedestrian navigation for people who are blind or low vision, available as a stand alone device or smartphone app (Sendero, 2015). The company has focused recent efforts on an improved point of interest (POI) database and a social community designed to encourage sharing of routes and new POIs (Morton & Yousuf, 2011). There are known limitations, like slope information, where to cross streets, and details about traffic lights and stop signs. Other companies have also entered this market but there is still room for new features and integration. For example, there are opportunities to incorporate additional information present in other systems, like transit vehicle arrival times, to improve pedestrian route planning (e.g., Schweiger, 2003).

An alternative approach is to utilize infrastructure supported guidance, usually through directional remote infrared audible signs (RIAS) anchored to infrastructure and vehicles (e.g., Crandall, 2015; Golledge, 1998). These have been deployed downtown San Francisco near the civic center at street crossings and select transit stations. The main weakness for such systems is their cost relative to their benefit (Petrella, 2009; Miller, 2012). RIAS is considerably more expensive to deploy than QR and wireless tag approaches or generic smartphone localization.

Another approach is to integrate a smartpen with tactile maps to provide spoken labels and guidance (Kehret et al., 2011; Miele and Landau, 2010). The smartpen technology is much cheaper than RIAS, does not require embedded infrastructure, and uses commodity hardware. However, this technology requires information preparation for each deployment on special paper.

Sidewalk surface materials have also been identified by several research teams as being especially important in pedestrian travel. For example, certain concrete surface treatments can create unwanted vibrations in wheelchair seats during travel. Technologies for addressing surface quality, both in construction and in maintenance, remain a unmet need. New technologies and research on this topic are discussed in the **[INNO]** and **[ARR]** documents.

3.3 Automation and Robotics

While industrial robotics and plant automation are well-established fields, there are few systems in regular contact with the general public from this domain. Some specialized systems are relevant to ATTRI stakeholders and are discussed below.

3.3.1 Transit

Transit has significant promise for the application of automation and robotics. Many train systems are already heavily operated, so automation is not a new area for service providers. More consistent environments, high passenger volumes, and the high cost of transit infrastructure also leads to a more cost effective application of autonomy and robotic technologies. This section examines two examples that have direct value to ATTRI stakeholder groups.

3.3.1.1 Docking

Dwell time, or the time spent at a stop for loading and unloading passengers, has a significant impact on public transit efficiency. Therefore, technologies to support accurate and high-precision docking-to-stop infrastructure is becoming increasingly common. Good docking leads to tight spacing between the vehicle and the curb or platform, thereby reducing the size of gaps and the need for bridge plates or ramps.

In some train systems, like sections of the Paris Metro RER, accurate docking is a requirement since train and platform doors must be aligned. In other systems doors align with markings on the platform, thereby allowing waiting passengers to position themselves for quicker boarding. This also helps prevent disoriented passengers from falling onto tracks or being struck by trains. Full-height installations reduce noise pollution and reduce wind, which can also help stakeholders who have difficutly with balance or loud stimuli.

For trains, docking is simpler since the only dimension of concern is along the path of travel. Bus distances from the curb or platform can vary greatly, thus increasing the challenge of precision positioning. Guide wheels to support driver steering are used in some bus rapid transit (BRT) systems. For example, the Cleveland HealthLine and the EmX BRT in Eugene, Oregon use such devices (Pessaro & Van Nostrand, 2011).

In non-BRT bus routes, docking is often dependent on the roadway geometry at a stop and road congestion. There are strong scenario pressures to leave the tail of a bus in the lane of traffic, thus ensuring the bus will be able to rejoin traffic without a long wait. Thus, road infrastructure elements like queue jumps and bus stops on the far side of signalized intersections can reduce the incentive of docking at an angle.

Parking enforcement at stops can also ensure adequate room for buses to dock with a curb. Many municipalities utilize high cost penalties and fines (i.e., over $100) to discourage parking that interferes with bus docking.

3.3.1.2 Personal Transit Vehicles

There are numerous examples of personal transit vehicles, sometimes called personal rapid transit (PRT) or Automated Transportation Networks (ATN). These utilize smaller, automated vehicles or PodCars to bring riders between selected points along a route or in a network. The vehicles only stop at destinations requested by the vehicle’s occupants, thereby allowing faster trips. Vehicles of this type usually operate in protected lanes, constrained areas, or guideways, thereby decreasing the challenges for autonomy but at the expense of requiring significant infrastructure support for unmanned travel. Well known examples of PRT include deployments at the West Virginia University (2015), Heathrow Airport (Ultra Global, 2015), and the *2getthere* implementations at the Masdar Institute (2015) and Schiphol Airport (2015).

Since both the vehicles and stops are designed as an integrated system, there are opportunities for at grade boarding, precision docking, and adequate maneuvering space for wheelchairs. As with light rail and other transit infrastructure, this is not always the case and physical barriers can be present if not designed properly.

3.3.2 Personal Vehicles

There are several commercially available vehicle control and safety systems on the market which are valuable to ATTRI stakeholders. Advanced and non-advanced control features include: motor-operated car seat lifts, backup cameras and blind spot warning systems, keyless entry and keyless ignition, automatic transmissions, automatic locks and windows, adjustable pedals and cruise control (Perch, 2013; CarsDirect 2014). Parking assistance, collision warning, and lane-keeping systems are the most relevant advanced and semi-autonomous vehicle control systems (Steinfeld, 2008; Roosemalen, et al 2010).

Assistance with parking can help by mitigating challenges in vehicle manipulation and situation awareness. Obstacle detection while backing up, rear-view video screens, and park assist autonomy are all useful and widely available in higher end cars. Semi-autonomous parking also relieves cognitive load by transferring path planning and steering wheel management to the vehicle, thereby allowing the driver to spend more time focusing on possible obstacles and their overall situation awareness. Current market systems are not fully autonomous since drivers are still required to supervise parking spot selection and intervene when safety risks occur. However, some implementations of these systems can create risk of over-reliance and improper mental models of system performance. Examples are documented in a NHTSA report to Congress (2006).

Collision warning systems (CWS) have promise for people with perception or cognition difficulties. Older drivers can encounter difficulty at night due to glare and other visual limitations. Forward looking sensors can increase awareness of oncoming threats, theoretically leading to more advanced warning and time to react to danger.

Adaptive cruise control (ACC) has similar value in that it can reduce the need for physical intervention. This can be valuable for people with reduced dexterity or who use hand controls for pedal actuation (Peters, 2001). Less pedal activity means less manipulation of vehicle control surfaces. Lane keeping assistance has similar value but, like backover avoidance technology, run the risk of serious harm if drivers utilize the wrong mental model during operation (e.g., Kierstein, 2014).

3.3.3 First / Last Mile

While not semi or fully autonomous, there are numerous commercial systems easily viewed as “robotics-ready” due to their ease of modification. Electric golf carts are popular with the robotics community as platforms for human-scale mobile robots. Golf carts are already used for first / last mile trips within gated communities, and sometimes along public sidewalks and shoulders in locations where such travel is legal. This tends to be a popular use case scenario in certain regions of the United States, specifically in certain southeastern U.S. communities.

The closest product to a purpose-built robot for first / last mile travel are the Segway and similar motorized systems. The Segway is also readily modified for semi and fully autonomous motion but there appear to be no commercial products of this type with extensive autonomous capability, leading to a unmet technology gap.

3.3.4 Pedestrian

Like electric golf carts, power wheelchairs and scooters are also frequently used as platforms for mobile robotics due to their easy modification. There is evidence that some people without disabilities will elect to use these devices in certain contexts, which can achieve an economy of scale for the service, but also present a burden on the service if such alternative uses are not properly anticipated and mitigated. For example, tourists without disabilities are known to rent scooters on the Las Vegas Strip due to the heat and long distances between hotels and casinos. This creates problems for visitors with disabilities who encounter reduced availability of rental scooters. This indicates gaps either in policy or policy enforcement, which technology may or may not be suited to address.

Automation and robotics involve extending a human’s perceptive and actuation capabilities. Many of the ways in which such technologies can assist pedestrian challenges have already been mentioned in improving wayfinding and navigation and in personal mobility.

3.4 Data Integration

This technology area includes solutions that enable the integration of data and information systems to create new accessible transportation applications. This technology area has two main aspects: (1) information that travelers with disabilities need, and (2) information that travelers with disabilities can provide. Travelers with disabilities need in-depth accessibility information about points of interest (POIs), infrastructure, facility amenities, terrain and surface types, and potential obstacles, integrated with maps and other information for their intended route. The SOP is that there are glaring data integration gaps in the technologies that can provide such services. To leverage the above information, a traveler with disabilities should be able to provide his or her specific requirements so that personalized assistance can be provided. To facilitate reuse and sharing, such personal requirements can be stored as a personal and private profile that can be accessed and updated by that person and their trusted caregivers, and used anonymously by algorithms that find the services that match the person's requirements. Personal preferences for using a single service as well as span multiple services can also be saved, updated, but also shared anonymously. Such information can be useful both to persons with similar or dissimilar disabilities, but whose information needs coincide for certain aspects of a specific mobility challenge.

The present state of the practice does not permit personalization and access to information of relevance to personal needs to the fine level of detail that will facilitate greater use of fixed route transportation services. For example, a service like Google StreetView may contain annotations of wheelchair accessible ramps for a building, but not the grade, width and boarding platform to vehicle gap information. Such information can be essential for a person who uses a certain model motorized wheelchair, for example. While there are technology gaps that need to be addressed, data of relevance to accessibility is being documented, collected and made available for use by third parties. We review some of those efforts in this section.

Requirements for types of data, its quality, and its uses, vary considerably over time and across user populations. Data integration considerations include but are not limited to: user needs, policy, standards, technical implementations of the standards, technical and applied research, the information ecosystem and the business models that maintain it.

3.4.1 Cross-Cutting

3.4.1.1 Open Information

In the summer of 2010, a diverse team was convened by the White House Office of Science and Technology Policy to explore how transportation data and other geo-data can be used to increase accessible travel by people with disabilities (Geo-Access Challenge Team, 2011). A general consensus formed around a strong need for integrated information; riders want the ability to link points of interest, travel data, and municipal infrastructure in order to develop a full picture of what they might expect when executing a trip.

While some of the suggestions from the Geo-Access team were specific to real-time information, many of the recommendations centered on data integration and open information resources for developers. The recommendations are:

"User Needs Research – Produce an annotated bibliography from existing sources of user needs covering the full range of accessible public/private transportation and municipal points-of-interest, and pursue additional research studies where necessary.

Information Ecosystem & Business Models Research – Pursue research studies on how accessible public/private transportation and municipal POI information is created, collected, aggregated, integrated and utilized by authorities and citizens/consumers. Also, leverage local public-private partnerships experienced in this area to research the various business models that enable cities and regions to offer location-based information and services.

Policy – An institutional and policy assessment – including ramifications related to information security and privacy – should be conducted to include three kinds of data required to enable transformation: Transportation Data (including Accessibility), Municipal Infrastructure Data, and Point-of-Interest (POI) Data. The Geo-Access Challenge Team recommends following up the assessment with a Federal Role paper that defines the rules of engagement between different agencies, open data guidance and an information security and privacy white paper to govern these initiatives.

Standards – Enhance existing standards or develop new ones to support structured data collection, aggregation, exchange, and interoperability for accessible transportation, relevant municipal infrastructure, and municipal points-of-interest (POIs), to support innovations in location-based information and services.

Data Environment Development – The data environment to support structured data collection, aggregation, exchange, and interoperability for accessible transportation, relevant municipal infrastructure, and municipal points-of-interest (POIs) needs to be developed, tested, and refined.

Technical & Applied Research – Once policy, standards, and data environment are developed, technical and applied research needs to be encouraged and supported to enable development of innovative applications and solutions. A state of the practice and innovation scan should be undertaken, and technical demonstrations and near-term / long-term development of applications should be supported.

Technology Transfer & Implementation Support – Novel approaches for transferring the enhanced geo-data policies, standards, and data environments into wider usage in both public and private sector arenas should be supported." (pp. 1-2)

A more recent analysis of open data practices within the transit industry by Schweiger (2015) suggests progress is being made on providing at least some of the data desired by the Geo-Access team. This analysis conducted a deep review of how transit agencies release open transit data, the barriers they encounter, and best practices. Key findings include: open data benefits transit agencies and their customers, legal fears have not been realized, dialog with data users is important, and the practice requires both management-level support and internal resources to ensure high quality data.

While there are other transit information standards, the most common format, hence a de facto standard, used by most developers is the General Transit Feed Specification (GTFS, originally known as Google Transit Feed Specification; Google Developers, 2015) and the new GTFS-Realtime extension of the format. This is the same format required by Google for inclusion in Google Transit, which in turn, drives many transit agencies to use this format for public release. Over 900 agencies worldwide release their data in this format (GTFS Data Exchange, 2015).

Unfortunately, other desired data sources, like municipal infrastructure data, are still very difficult for developers to acquire at large scale. This technology gap may be partly due to legacy data systems, including paper records, and legal fears similar to the ones raised in the transit industry (e.g., Schweiger, 2015). Some cities are farther along than others, with New York being an excellent example of what can be accomplished with significant resources over time (NYC Open Data, 2015). Smaller cities with less resources are also active in this area (e.g., Pittsburgh, 2015).

3.4.2 Transit

A review of data integration within the transit industry (NCMM, 2013) suggests that the rapid development of transportation applications is linked to open data from transit agencies and an increasingly refined understanding of how this data can be used. In the report, they note there were 55 apps using data from just TriMet in Portland, Oregon of which none were created by the agency itself. The authors suggest (1) integrated real-time transit information and display format preferences can help riders plan and use community transportation options more effectively and (2) such information may remove barriers to people with disabilities from taking public transit or sharing rides and vehicles.

Unfortunately many apps and smartphone friendly websites are not accessible (NCAM, 2012) and the general accessibility problems associated with modern web development trends and smartphone software suggest that a digital divide is developing between those who need accessible interfaces and those who do not. It is clear that the potential for personalized and accessible transit information has yet to be fully achieved.

3.4.3 Personal Vehicles

As in the transit modality, real-time information is also having an impact on drivers' ability to find parking spaces and the management of traffic networks for congestion. Parking information reduces time spent driving around urban centers, thereby lowering exposure to adverse events, congestion, vehicle emissions, and the cognitive load associated with added driving and finding a parking spot. A good example of this is ParkPGH, which uses historical parking and event data in a prediction model to provide real-time information on the availability of parking at multiple garages in the Pittsburgh, Pennsylvania, Cultural District (ParkPGH, 2015; Fabusuyi, et al 2013).

The system provides a mobile website, iPhone app, SMS, and phone options for accessing parking information. In addition to showing garage fullness, the system integrates garage details (e.g., rates, hours, etc) and local POI data for easier pre-trip planning and real-time exploration while en-route. Since the Cultural District typically draws groups, it is common for cars headed to local POIs to have passengers who can safely check garage fullness for the driver.

Fabusuyi, et al (2013) collected pre and post deployment evaluation data and found ParkPGH made it easier to find spots and reduced search time for almost half of the system's users, in some cases leading to reductions of over 6 minutes. The estimated impact of the system on drivers during this evaluation, due to time value and gas expenditure, was over $127,000.

Automated parking garages can permit significant door and ramp clearances for people with disabilities. Patrons exit their vehicles at the entrance and the car is removed on a pallet. This also benefits older adults since they do not need to look around sharp corners, deal with large fluctuations in lighting, or follow ambiguous pavement markings and signage. One possible concern for people with disabilities are vehicle dimension requirements. For example, a garage may not be able to accommodate a full size wheelchair van due to height restrictions. Since these systems require real-time knowledge of space occupancy, it would be straightforward to integrate data from a garage with information apps like ParkPGH.

For street parking, there are many systems now on the market designed to support meter payment remotely through smartphone apps. This adds convenience for people who do not want to go back and forth to parking spots due to inclement weather or limited mobility. Time expired alerts, auto refills, and guidance back to the parking spot are also available in many apps. In some cases, these apps also allow map filtering to only show locations where ADA spots are located or the system believes there are available spots (e.g., Streetline, 2015). This last step is important for wheelchair users and people seeking to minimize pedestrian distances. Some apps also support pedestrian guidance back to the car.

3.4.4 First / Last Mile

A key problem in planning travel along the first / last mile is identifying how transit trips interface with pedestrian and other local modes of travel to reach a desired destination. IBM's AccessMyNYC demonstration (AccessMyNYC, 2012) explored this concept. This smartphone friendly website allowed users in New York City to find and plan transit or walking routes, identify accessibility information about points-of-interest, and then share their views using ratings and Twitter. While the initial version was a short-term demonstration, it showed the power of this type of integration and is now a product marketed to cities as Access My City. There are a number of less integrated apps that focus on just the accessibility of points-of-interest, stores, and other facilities (e.g., IBM Accessibility City Tag, Wheelmap, CitiRoller, OpenStreetMap, etc.).

While not public transit, there are also numerous private transit systems in use by companies to help employees and visitors bridge the first / last mile. Common examples include hospital and university shuttles, airport and theme park shuttles to and from parking lots, etc. Some systems include real-time arrival information and other ITS information systems. It is unclear how many of these vehicles and systems are accessible.

3.4.5 Pedestrian

Applications integrating Google StreetView into navigation guidance allow people with disabilities to scout ahead and look at curbs, etc. There are also anecdotal stories of people using StreetView to find business' phone numbers (displayed on signs outside storefronts) so they can call for the store's accessibility information.

Many local municipalities and commercial business districts provide neighborhood map kiosks with integrated information about POIs, transit stops, sidewalks, and parking options. However, most of these maps are static, printed, and largely inaccessible to people who are blind or very low vision. In some cases, these maps are also placed in locations that are inaccessible to seated users or those of short stature. Some organizations provide paper, PDF, web, or smartphone alternatives with varying degrees of accessibility.

Some venues are starting to explore the use of bluetooth beacons to provide precise location-specific information, rather than relying on the less accurate phone localization subsystems. For example, MLB's Ballpark app allows users to pinpoint their location in ballparks, purchase food from nearby vendors, and see location-specific advertisements and coupons. It is likely that these sorts of hyper-local experiences which merge georeferenced data will become increasingly more common.

One subtle, yet potentially very dangerous data integration problem centers on signal preemption at wide intersections. If a transit or emergency vehicle triggers a signal phase change for a very wide road, then it is easily possible for a slow moving pedestrian to be caught in unsafe territory. There are pedestrian detection systems entering the market but tight integration between signal preemption and these systems is limited. DSRC based solutions may also help mitigate risk of a slow moving pedestrian being hit if the pedestrian is carrying an equipped phone or beacon.

Another example are lights that vary the length of yellow phases based on whether a pedestrian crossing button has been pressed. Pedestrians are typically unaware that such changes may occur and those who move slowly may find themselves unable to safely cross a wide road if the light turns yellow shortly after they began crossing. Again, this is a scenario that DSRC may help mitigate this gap.

3.5 Enhanced Human Service Transportation

As mentioned at the start of this document, human service transportation is oriented for clients of a specific human or social service agency. The two ATTRI stakeholder groups of older adults and veterans with disabilities will likely find many of their challenges articulated in this section more so than for people with disabilities who are not part of either group. Tendencies among older adults are to age in place, which is often in suburban or rural areas that are typically not well-served by fixed-route public transit. Similarly, much of veteran housing is developed in suburban or rural areas where land is inexpensive but lacks proximity to vital neighborhoods that can be a source of economic participation and self-sustainment for the veterans who live there. Older adults may choose to give up driving yet desire to maintain an active life which involves: caring for grandchildren, volunteering, attending civil, religious and social activities and events, and convenient access to medical care and services. Veterans with disabilities are most likely still of working age and desirous of accessing and participating in the local economy, communities and medical services.

Privacy, reserve, and schedule mismatch are often reasons given for not requesting rides from neighbors of either stakeholder groups, and often, persons of these groups have no prior experience using fixed-route transit, which can be an additional inhibiting factor. Paratransit also has service issues. It has a higher cost per passenger mile to operate, requires 24- to 48-hour advanced notice to schedule a pickup, is often deliberately over-scheduled with the anticipation that a certain percentage of ride requests will be canceled, is unpredictable about when it will arrive to pick up for a return trip, and hence adds significant constraints so that transit is the activity that must be planned for and scheduled rather than something that facilitates access to the main activity of interest.

Many service options are constrained to specific populations due to financial policies. An unintended consequence of services being focused on a specific group is that sometimes there is not a critical-enough mass of users to make the services offered cost-effective (Quadrifoglio, 2013), and that other potential users who could be covered by the service, are not. It is worth noting that public transit in the U.S., in general, is often organized by a multitude of urban, suburban, and rural carriers who may be specialized for a particular mode (e.g. light rail, train, coach, fixed-route bus, etc.). In this respect, addressing the needs of human service transportation through the vision of *enhanced* human service transportation, is an example and opportunity where the guidance of universal design is particularly applicable. In the EHST context, universal design encourages the solution for one target challenge to be considerate and inclusive of other possible and likely user groups. The same transit solutions to, for example, recreational areas for older adults and veterans with disabilities could also apply to, say, middle and high school students for after school sports and activities. Through the increased ridership of transit services that are able to accommodate these rider types, an economy of scale can be achieved that enables the services to operate more efficiently and cost-effectively than paratransit alone by virtue of it having a critical mass of ridership.

The needs of the transit user may involve the use of multiple transit modes, yet the interfaces between modes may not be particularly well-designed. Often, evidence of poor interface design between two service providers is in the use of different fare payment systems, accessibility services, and mismatched departure and wait times. Sometimes the reasons for the poor interfaces are due to the equipment that was acquired to perform the service, but most times it is due to policy (Quadrifoglio, 2013). For example, Jonnalagedda, et al. (2014) noted challenges for persons with visual disabilities at airports that are determined by policies or procedures: (1) the need to walk to the airport from a car as opposed to being escorted by the driver, because there is a security policy of not allowing cars to park at the airport curb, (2) passing through airport security, and (3) needing a paper ticket to board a bus, which cannot be meaningfully read by a traveler who cannot see.

In the sections that follow we summarize and highlight existing practices of enhanced human service transportation [EHST].

3.5.1 Cross-Cutting

3.5.1.1 End-to-end Multimodal & Interregional Trip Planning

One of the longest standing and very well-established free multimodal and interregional trip planning services is offered by the San Francisco Bay Metropolitan Transportation Commission’s 511.org (2015) phone service and web site. The phone service is a speech recognition and generation interface to the web site. The web site is presented to facilitate its traversal via screen readers for persons who are blind or visually impaired. 511.org offers a single point of reference for getting around the San Francisco Bay Area, facilitating a person’s ability to:

- plan a commuting or leisure trip, either with or without a transit planner,
- finding the best options for getting to specific points of interest, such as the airport and tourist attractions,

- monitor current traffic conditions,
- know bus departure times and transit disruptions,
- provide maps of bicycle and pedestrian paths, as well as locations of bicycle share pickup and dropoff stands,
- form an ad hoc carpool and a means of identifying the vehicle for toll discount eligibility, and
- download smartphone applications ("apps") that are created by the authority as well as third party vendors; the portal publishes software libraries to its data streams that third party developers can use in their programs.

One of the services is the *Enhanced Trip Planner*, which allows a user to generate multiple trips of the form: "Drive Only", "Drive to Transit", and "Transit Only", in multiple modes (e.g. drive, park, walk, bus, metro, etc.). Each trip can be compared to each other in terms of estimated duration and arrival time for a given departure time, how much each trip costs monetarily, and how much each trip costs the environment in terms of carbon generated. Preferred trips can be saved to a personal profile and reused on multiple occasions, updated with the current travel times. For each saved trip, a person can set and receive e-mail and text message alerts.

A 511-like service is very important for all ATTRI stakeholders because it renders multimodal and interregional trip planning significantly easier. It is easier to plan appointments and their return trips, a full day schedule can be planned that includes multiple trips, and it allows for the experience of previous trips to be saved and reused with updated information. The technology gap for most 511 options with respect to ATTRI stakeholders is that the services and planning assistance that it provides is not yet updated to accommodate the end-to-end travel of persons with disabilities due to the unique and personalized needs of each individual.

For example, a person with a mobility disability might prefer using a motorized scooter of a certain dimension. Not only should the trip planner indicate the stations that the person can board, the locations of the access ramps or elevators that can accommodate the scooter, but also if boarding and securement is feasible in the desired transit vehicle. At the minimum, users should be able to see what vehicle type is assigned to a specific route, much like planes for commercial flights. Many transit lines use a mix of vehicle types and not all vehicles will necessarily have the same configuration.

Similarly, persons with cognitive and vision disabilities need to be able to download a virtual trip, complete with appropriate landmarks for their capabilities. The preferences for what cues and landmarks the person can easily identify are unique to the individuals, but there would be a need for making such annotations in a user profile and for the transit services that are offered.

Another issue is discovery of services. Stakeholders may have trouble determining which service providers and options best fit their constraints. This issue is especially important for veterans due to eligility factors. The Veterans Transportation and Community Living Initiative (VTCLI) seeks to address this issue by fostering “one call” information centers in local markets. This initiative also links transportation with other services, like health care, work, and education.

3.5.1.2 Integrated Payment Systems

In the U.S., in particular, many different authorities, private companies, and regional transit systems are involved in offering multiple transit service options to their riders. One of the difficulties that many transit users have in using multiple modes of transit is that of understanding the charges, when the charges are applied, and the form of payment that is accepted as fare. While cash may be the simplest and most ubiquitous form of payment, most transit vehicles either do not accept or do not have the ability of returning change to users in the event of overpayment. Further, even those machines that offer fare payment in cash may impose restrictions on the form of monetary payment: bills only, bills and quarters, no pennies, etc.

Some transit systems introduced alternative forms of vouchers designed to simplify the fare collection process: tokens, paper tickets and transfer vouchers, and credit card like passes of multiple forms. Yet, many times these alternative forms of payment are unsuited for use by older adults and persons with disabilities such as persons with visual and cognitive disabilities. Tokens can be confused with coins, paper tickets can be difficult to read, and transit cards, particularly if one needs to use more than one, can be confusing and it may not always be clear what is the appropriate context in which to use them.

For this reason, this section mentions some services that put into practice the types of integrated payment systems that are amenable to ATTRI stakeholders. Examples of such integrated payment systems include the San Francisco Bay Clipper Card, Transport for London Oyster Card, Korean T-Money Card, Washington Metropolitan Area Transit Authority’s SmartTrip Card, and Maryland Transit Authority’s CharmCard. The latter two transit authorities recognize each other’s respective integrated fare cards.

3.5.2 Transit

Thatcher, et al (2013) present a strong case for avoiding the use of paratransit service as the default for people with disabilities who can utilize fixed-route transit options. They cite lower costs for both the rider and agency, more spontaneous travel, and more flexibility. In addition to these operational benefits, utilization of fixed-route transit is a form of mainstreaming, thus leading to greater awareness in the general public of people with disabilities which may result in improved inclusion and mobility options. The authors cite a variety of reasons why paratransit use is growing, including increased travel in general, issues with inaccessible bus stops and infrastructure, inertia among riders, and a need for effective paratransit eligibility determinations. While the report was limited in its discussion of technology, it did detail strategies for shifting riders from paratransit to fixed-route transit which may provide guidance on opportunities for technology intervention. A few examples which could be addressed through technology are provided below:

- Promote fixed-route transit use prior to aging into a disability and make accessibility details visible on the agency website. Some agencies utilize positive examples and lists of advantages for use of fixed-route. (p.69)
- Promote travel training to encourage use of fixed-route transit. This is a cost effective approach even though it may not appear so at first glance. (p.83)
- Include fixed-route travel training in paratransit evaluations, even though training cannot be a factor in paratransit eligibility. (p.76)
- Better stop announcements and route identification, especially at transfer points, major intersections, POIs, periodic locations, and requested stops. The authors note that, “It can be a safety risk if a rider with a cognitive disability, or who is blind or has a vision impairment, disembarks at a wrong stop.” (p. 36).
- Better route and destination announcements so riders can determine if they are going in the correct direction. (p.38)

3.5.2.1 Flex-Route Transit

While the exact implementation of flex-route transit varies, the general concept centers on buses which traverse regular or semi-regular routes but will deviate within a preset distance for on-demand passenger pickups and drop offs. This allows riders to reduce walking distances and in some case obtain door-to-door service without utilization of full-scale paratransit. This is clearly useful for ATTRI stakeholders in that it gets closer to point-to-point transit service with somewhat predictable routes and trip durations.

This can be especially powerful in rural regions where there is limited fixed-route service. For example, Skagit Transit (2015) in Burlington, Washington permits deviations off certain regular routes of up to 3/4 of a mile. Like paratransit, requests must be made a day in advance. DART (2015) in Delaware offers similar service with requests as short as 2 hours and deviations of up to a mile. HART (2015) in the Tampa region of Florida also supports requests as short as 2 hours in advance, but also allows walk-up options at specific bus stops and door-to-door service within a neighborhood zone.

3.5.2.2 Paratransit

Typically, this door-to-door service is booked in advance and is publicly subsidized. As the demand for paratransit services increases and availability of public funding decreases, there is a constant balancing act between maintaining a high quality of service while keeping the operations financially feasible. One of the key activities in striking this balance is efficient allocation of vehicles to service trips, especially over the myriad of events that make it difficult to anticipate how a schedule is going to have to evolve throughout its execution during the day. The effectiveness and efficiency of paratransit operations depends heavily on the ability to dynamically manage vehicle schedules in response to execution dynamics. Below, we will define what the paratransit management problem is and describe how the current state of practice addresses it. Note that poor management can result in poor service (late or missed pick-ups, long ride times) for the target population and/or providers being in financial jeopardy.

The paratransit management problem is an instance of the Dial-a-Ride Problem (DARP) (Cordeau and Laporte, 2003; Cordeau and Laporte, 2007). The objective in a DARP is to design vehicle schedules to satisfy requests for travel between pick-up and drop-off locations at specified times. Typically, as input, DARPs specify a set of requests, a set of available vehicles, and a set of constraints ensuring the quality of the service, e.g., time windows within which pick-ups must be made or maximum allowable ride time for a passenger. DARPs may be over-subscribed, i.e., not all requests can be serviced within their constraints, in which case the constraints may be relaxed in order to help accommodate the extra requests. There often are optimizing objectives for DARPs, such as minimizing cost by minimizing the number of vehicles used while allowing some level of constraint relaxation, or maximizing service quality by determining the minimal number of vehicles to satisfy the requests without relaxing constraints. Formally, there are two classes of DARPs, static and dynamic. In a static DARP, all the requests and the available vehicle are known up front. In a dynamic DARP, the requests are serviced as they arrive and the available vehicles can be increased. Most real-world DARPs are hybrids, with a majority of the requests but not all being known up front and there mostly being a static number of available vehicles but extra ones are available at a cost.

There are a few different types of requests. Subscription requests are recurrent ones over a week or month and are typically known in advance of the day service. One-time requests are for a specific trip and often are known only in advance due to many providers not supporting same-day service. The one exception allowing same-day service is “will call” requests, where passengers do not know the exact time of a return trip, e.g., for a doctor’s appointment. These requests are handled dynamically as soon as the call is received to pick up the passenger.

The number of available vehicles is also known in advance. There are different types of vehicles available, each providing capacity to carry a specified number of passengers. Some types of vehicles provide wheelchair capacity, while the others have strictly ambulatory capacity. In the former case, wheelchair capacity can be converted to ambulatory capacity, so the overall carrying capacity will vary depending on how the wheelchair capacity is used.

Two typical service quality constraints for paratransit are the following:

Pick-Up-Window Constraint - This constraint on the window of time it is permissible to pick up a passenger is relative to the time that is negotiated with the passenger for his or her pick-up. An example constraint would be that a pick-up should not occur any earlier than ten minutes before the negotiated time or any later than twenty minutes after the negotiated time. Another would be that, for “will-calls”, the pick-up should occur no later than forty-five minutes after receiving the call.

Ride-Time Constraint - This constraint limits the amount of time a passenger should ride on a vehicle. An example constraint would be that a passenger should not ride longer than the maximum of twenty minutes and the minimum of two hours and twice the estimated time to go directly from the pick-up to the drop-off.

Providers are allowed to relax these constraints, but, overall performance is usually based on meeting them. In the case of a private provider, if these constraints are violated too often or by large magnitudes, the provider often risks having its service area reduced or losing its contract. The goal for the provider is to meet these constraints while minimizing the resources it needs to use.

Typical operations for a provider start with generating a solution, i.e., a set of vehicle schedules to the DARP for the following day’s requests. The solution is generated either manually or through automated scheduling software in order to create base schedules to use at the start of the next day. Complicating this process is that, on average, there is a large, e.g., 15%, request cancellation rate that occurs during the day of service. The human schedulers actually over allocate the vehicle timelines in anticipation of these cancellations. That is, the start-of- day schedules would require frequent relaxations of the constraints if they were to execute as scheduled, so the schedules start with a number of trips that are already in jeopardy of missing their service constraints. It is left to the Dispatchers to resolve these problematic trips as cancellations arrive.

Although an advance reservation policy enables the a priori development of a daily operations schedule, unexpected events that occur as execution proceeds (e.g., vehicle breakdowns, traffic accidents, “will call” requests, trip cancellations) quickly force changes and degrade the quality of originally planned vehicle itineraries. In current practice, often Dispatchers responsible for coordinating the movements of a service provider's vehicles respond to these events in a fire fighting fashion. Since the start-of-day schedule becomes an increasingly distant reference point as the day progresses, they often become aware of problems (e.g., potential late pickups) late, restricting their ability to effectively respond. Although some Dispatchers have visibility of the real-time location of vehicles, they often must make decisions to redirect vehicles without good understanding of the downstream consequences to subsequent trips scheduled for various vehicles. During peak request periods, the Dispatcher can often become overwhelmed due to time pressure and decision complexity. Ultimately, the quality of decisions depends heavily on the Dispatchers expertise, and it is difficult to find and retain experienced personnel in this position. As a result, the decisions that are made are often suboptimal with respect to maximizing customer quality of service, and this has a cascading effect through the day.

There are a number of commercial software offerings available to address the Paratransit management problem. Some of the major players are Trapeze's Paratransit Scheduling System (PASS), RouteMatch's Demand-Response and Paratransit Scheduling, Stratagen's ADEPT Scheduler, and Ecolane's Demand-Response Software. While it is difficult to determine exact capabilities of these software packages due to them protecting their intellectual property, we can roughly characterized them along the following dimensions:

Dynamic Scheduling - the capability to adapt the vehicle schedules on the fly to meet emergent problems/requests. Routematch explicitly touts its ability to keep schedules in sync with execution by continuously optimizing, although it is unclear at what resolution it does this optimization. Ecolane's scheduler is capable of re-solving the entire schedule when online dynamics indicate, but it requires a period of time for a near horizon in which the *schedule* cannot change. It is not clear how much dynamic scheduling is done in PASS and ADEPT. All of these packages provide some notification of pick-up times to clients, i.e., give multi-mode alerts (email, SMS text, etc.) for when pick-ups are expected.

Decision Support - the degree to which the scheduling software includes humans in the loop. Schedulers range from being totally automated to providing decision-support for human dispatchers. For example, Ecolane limits humans in the loop by running autonomously, constantly adjusting the schedule as execution-time dynamics occur. Drivers are required to perform the pick-ups and dropoffs in the order specified by the schedule. New requests are automatically inserted into the schedule. The more decision-support schedulers provide options for where to insert a new request, even allowing for manual insertions.

Dynamic Monitoring - the degree in which a scheduler incorporates execution-time updates into the schedules to maintain best guesses for when future service (pick-ups and dropoffs) will be provided. Most of the packages do provide some updating on when service will be provided as execution unfolds. One related issue that affects the value of updating is how the over-subscription of the initial schedule is maintained. For example, Ecolane accommodates the extra requests by, essentially, assuming that the vehicle travels faster than it will in reality. The updates in that model are subject to the same error until more realistic durations are enforced.

3.5.2.3 Taxis and Shared Vehicles

The issue of wheelchair accessible taxis has been a point of contention for people with disabilities. Inherently accessible taxi vehicles exist and have been on the market for many years. The most well known in the United States is the MV1 (2015), manufactured by AM General. These vehicles are popular with taxi companies which target people with disabilities as customers. An example is VETaxi (2015) in Pittsburgh, which takes the added step of employing veterans and military family members as drivers. Some cities have fully accessible taxi coverage, like London, where all black cabs are wheelchair accessible (Gov.UK, 2015). Some also have hearing aid induction loops.

However, some entities have interpreted the ADA as not requiring wheelchair accessible vehicles in the United States. Local advocates still push for more accessible vehicles, including high profile court cases. New York City recently settled a lawsuit over their new taxi vehicle standard, which was not wheelchair accessible (Brown, 2014). This agreement will lead to 7,500 wheelchair accessible vehicles by 2020, which would correspond to half of the taxis in the region. Currently, only 600 wheelchair accessible taxis are in service.

The International Association of Transportation Regulators recently published model regulations for accessible taxis and for-hire vehicles (Daus, 2014). Some of their observations demonstrate a desire to increase service quality and coverage through technology. To some degree, the taxi industry is still reacting to the impact of transportation network companies (TNCs) like Uber and Lyft, both through legal efforts and the introduction of new technology. This creates an interaction effect with the generally low coverage of wheelchair accessible taxis. For example, San Francisco only has 100 wheelchair accessible taxis, which corresponds to about 5.3% of the total fleet (Said, 2014). Supply is further constricted as a result of competitive pressure from TNCs. The number of wheelchair pickups by taxis in San Francisco has been dropping precipitously, partly due to difficulties in getting taxi drivers to commit to the program due to perceived higher costs while also under pressure from TNCs (Kwong, 2014).

Unlike taxis, TNCs are not explicitly regulated under the ADA and there is disagreement over what kind of regulation should exist to support people with disabilities. These issues are still in flux as there is a patchwork of lawsuits and policies governing TNCs across the country (Cowan, 2014). While there are efforts to require TNCs to file accessibility plans, maintain a fleet of ramp accessible taxis as a percentage of their vehicles, and to train their drivers, regulations and laws at the local, state, or federal levels are still in early stages (e.g., NCSL, 2014).

During the course of this work, the team reached out to representatives at both Uber and Lyft to get insight on how their services interact with people with disabilities since there have been reports of discrimination by TNC drivers. Details below are drawn from these conversations. Both companies have internal policies in place to support riders with disabilities which, in some cases, are influenced by negotiated agreements with states and local municipalities (e.g., Portland, California, etc). Therefore, aspects of their policies can be viewed as reflections on other stakeholder needs and desires.

Uber and Lyft explicitly prohibit discrimination against people with disabilities. Riders and drivers are included in both companies' policies and violations of the policies may lead to account deactivation. Lyft's policy includes explicit details on service animals and stowable wheelchairs, along with advice for drivers on how to support such customers and emergency phone numbers for case assistance (Lyft, 2015). Their policy also covers drivers with service animals.

Both Uber and Lyft partner with local transportation providers who have wheelchair accessible vehicles. Some of these providers are non-government, non-profit organizations. Riders are referred to these vehicles, as some Uber riders are referred to taxis or limousines. In some cases, riders are required to make requests 24 hours in advance which is similar to regular paratransit service. Uber is interested in how their service model compares to traditional paratransit service but notes the common challenges of limited wheelchair accessible vehicle supply.

Uber has received positive feedback on the cashless nature of the payment model from riders who are blind. This helps mitigate conflict and increases safety among the participants. Likewise, Lyft has worked to ensure VoiceOver capability in iOS for a better screenreader experience. Both companies cite the value to real-time arrival alerts for riders.

In cooperation with the organizations focused on the needs of people who are deaf, Uber has also recently updated their driver user interface to better support drivers who are deaf or hard-of-hearing. This helps remove barriers for such drivers, thereby increasing opportunities to earn money. User interaction elements include: alerting the rider that their driver is deaf or hard-of-hearing, encouraging the rider to identify their destination in the app rather than speaking it to the driver, better non-audible notifications, and removing the option to call the driver when matched with a deaf or hard-of-hearing driver. Uber has also incorporated visual and vibration features into the app to better support riders who are deaf and have received positive feedback regarding the ability to enter a destination within the app. Lyft also actively recruits drivers who are deaf and hard-of-hearing, with good results (Jaffe, 2014; Said, 2015).

Uber has also reached out to veterans as a source of drivers through UberMILITARY (Gates & Kalanick, 2014), which has a focus of adding 50,000 veterans, service members, and military spouses as Uber drivers. Recent statistics indicate the over $35 million has been earned by drivers in the program (Uber Newsroom, 2015). The program also includes local chapters and a Family Coalition to support drivers in the program.

3.5.3 Personal Vehicles

Losing the ability to drive, either due to expense or capability, has a major impact on older adults who then need to transfer the task of driving to family caregivers. One novel service approach to serve this need is Independent Transportation Network (ITN) America (2015), a coordinated ride sharing for older adults. This model creates community networks in franchised regions where drivers can earn credit for their family members even if they live in different parts of the country. For example, an adult child in San Diego, California can provide rides for local older adults, which credits their parent’s account in Portland, Maine. Alternatively, non-driving caregivers can also deposit money in an older adult's account. Other funding mechanisms also exist, like car donations and gifts. To date, over 2.3 million miles have been driven in the ITN system.

3.5.4 First / Last Mile

In addition to identifying service strategies for fixed-route transit, Thatcher, et al (2013) identified barriers in the first / last mile, especially at bus stops. If a rider cannot board or exit a bus at their desired destination, then the accessible travel distance along the first / last mile for that stop is zero. Examples of barriers to accessible stop use highlighted by the authors include, but are not limited to:

- Inadequate landing pads at bus stops
- Difficulty to read bus route signs at stops
- Sidewalks that do not connect with bus stops

The authors also highlight the efforts of Montgomery County, Maryland to study bus stops and connecting pathways. They note a major objective was to reduce the number of pedestrian accidents and fatalities. Likewise, they note an increase in overall ridership and lift deployments for Intercity Transit in Olympia, Washington after improving the infrastructure at 24 stops. This evidence, combined with other examples, lead the authors to conclude that bus stop infrastructure improvements can have a positive impact on travel near connection points to public transit.

3.5.5 Pedestrian

Thatcher, et al (2013) also examined issues relevant to pedestrians which extend beyond just the first / last mile. Their observations capture many of the general pedestrian barriers encountered by ATTRI stakeholder groups and described in other literature. Examples include:

- Narrow paths of travel, cross slopes, and uneven terrain
- Curb ramps on only one side of the street
- Sidewalks obstructed by public amenities and utilities
- Over-growth of adjacent shrubbery
- Poorly maintained pavement
- Diagonal curb ramps that can steer low vision or cane users into the middle of the intersection

All of these potential barriers, and many others, can be captured and incorporated into GIS data structures for use in both wayfinding tools and infrastructure maintenance efforts. These are good examples of how low tech barriers can be mitigated through better open data. The challenge is gathering the data, continuously updating to prevent stale data, and providing the data in a form usable by technology developers. Technological solutions for this are needed.

4 Conclusions

In this section we summarize some of the key findings of this effort. Specific products are not identified in the summary below, nor are we explicitly endorsing products mentioned in the body of this report. It is more important to focus on features and functions since these are what directly address ATTRI stakeholder needs, which is the intent of this effort.

Wayfinding and Navigation

This technology area has already received significant attention by industry and service providers. However, transportation routing in modes other than personal vehicles remain complex and often confusing. External forces, like cost and out of date policies, can limit deployment of established best practice technologies. As a result, many new technology solutions are shifting in from infrastructure equiment to digital methods usable through smartphones and personal computers. In parallel, some technology gaps are increasing in impact due to changes in transportation practices. For example, pedestrians with functional issues in vision or mobility often have difficulty traversing roundabouts, which are becoming more common due to their impact on congestion.

Promising technologies

- Smartphone apps and websites for transit and pedestrian travel planning are common and readily available.
- In-vehicle navigation systems, websites, and smartphone apps are common and readily available for those who drive personal vehicles.
- Stop and train platform announcements presented in parallel over speakers and as text on screens serve a wide range of users and help with perceptual and cognitive disabilities.
- Pedestrian-only cycles on signal lights are especially helpful for intersections with complex layouts and high volumes.

Technology gaps

- Methods for incorporating user capabilities during transit and pedestrian trip planning are rare.
- Reliable and scalable localization that works underground or in GPS-denied regions is not widely available. Good localization is a requirement for navigation assistance.

- In-vehicle navigation systems often lack route preference settings that meet the needs of ATTRI stakeholders.
- Technologies are needed for addressing guidance during first / last mile traversal.
- Safe traversal of roundabouts remains a challenge.

ITS and Assistive Technologies

There are numerous specialized assistive technologies designed to mitigate barriers within transportation systems. While successful, many of these are niche products that serve a small population. Tension exists between aesthetic designs that create mobility barriers and designs that avoid the need for assistive technologies. Some assistive technologies remain very expensive, leading to increased value in universal design solutions. Technologies that embody universal design principles have broad value to all transportation users and greater value to those sensitive to functional barriers. For example, at-grade vehicle boarding helps people sensitive to mobility barriers but also allow other riders to board more quikly and safely. Therefore, there is a strong need to encourage universal design in new product and environment design.

Promising technologies

- Real-time transit information helps reduce uncertainty and wait times.
- Automated gap plates on light rail and subways assist the boarding process.
- Wheelchair securement and crash safety standards have been developed and adopted.
- Some in-vehicle displays offer a 360-degree plan-view of the area surrounding personal vehicles for better situation awareness.
- Power assist and power wheelchairs can reduce fatigue during the first / last mile and longer pedestrian routes.
- Bike share systems and bicycle storage on transit vehicles may have value for ATTRI stakeholders who have the capability to safety ride a bicycle.
- There are several GPS-based navigation options for pedestrians who are blind or low vision.

Technology gaps

- Better methods for managing large grade changes when boarding transit vehicles are needed.
- Many personal vehicles are still difficult to enter and exit by people who are older or have a disability.
- Vehicle modification is still very expensive.
- Technologies that support last / first mile and pedestrian travel by people with cognitive disabilities are needed.

Automation and Robotics

Technologies in standard practice for this area are largely centered on public transit. For example, some trains will align with automated doors at station platforms for added safety. Advances in personal vehicles and robots are expected in the near future, but are currently only available at the higher price points. There is significant promise in first / last mile travel due to slower vehicle speeds (safe neighborhood operation) and opportunities for low or no step entry (door-to-door service). However, these vehicles are often not autonomous yet, limiting their value to the functional areas of vision and cognition. There is also some evidence that these types of neighborhood solutions may be over-used by people without disabilities, leading to possible concerns regarding supply and demand.

Promising technologies

- Technologies for precision docking can make boarding and alighting easier.
- Rail platform doors can help prevent travelers from falling onto tracks or being struck by trains.
- Personal vehicles are becoming increasingly automated and intelligent, which potentially lowers effort and difficulty for certain users.

Technology gaps

- There is a gap in autonomous vehicles for the first / last mile. Most personal devices for this domain are not autonomous.
- Some shared-use mobility devices are over-used by people without disabilities, thereby limiting access to those who need the devices.

Data Integration

Some of the major successes, as well as gaps, in data integration are related to the availability of transportation information in machine-readable form. New information feeds by some service providers have increased accessibility and enabled third party transportation information apps and services. Conversely, some providers do not release information for policy reasons and a considerable amount of important information is stored either on paper or not at all. Transportation data has value to a wide range of stakeholders and technologies, so this is an important area to address through deployment funding and policy changes. For example, knowledge about where a bus is located helps (a) waiting riders limit exposure to inclement weather and plan alternate routes during travel exceptions, (b) transit providers maintain awareness about the state of their system and opportunities for planning improvements, and (c) traffic congestion technologies determine when a bus is expected to dwell at a local stop, thereby altering nearby traffic. Crowdsourcing may be the most cost effective approach for gathering and maintaining certain types of data. Public release of transportation and municipal data often spawns new services created, funded, and maintained by third parties. For example, third party developers have used public data to provide information services tailored to support specific functional areas, like mobility and cognition, free of charge to the public agency.

Promising technologies

- The number of relevant data sources is rising due to increased open data releases by public agencies. Successes include the rapid growth in transit apps due to the public release of schedule and real-time data by transit agencies.
- Crowdsourcing can be an effective method for filling information gaps, if implemented properly.
- Parking information and meter payment apps can help those with mobility and dexterity disabilities.
- Web-based map tools are helpful for scouting accessible routes and building entrance features.
- Bluetooth beacons can help provide low-cost localization inside buildings.

Technology gaps

- Some service providers do not release open data for use by third parties (e.g., some transit agencies). In some cases, the data is only partially released thereby limiting value and impact.
- Many data sources are stored in disparate locations and are hard to integrate into traveler information systems. Data quality, access rights, and use policies can vary considerably.
- Methods for acquiring and presenting data specific to the needs of ATTRI stakeholders are rare or lacking. Similarly, many mainstream traveler information apps are not accessible.
- Key data, like municipal infrastructure details, is either missing or stored in ways that make use by computer systems difficult.
- There is room for improvement on intelligent signal preemption and pedestrian crossing timing.

Enhanced Human Service Transportation

Many new and existing examples in this technology area center on support for the cognitive functional area. Coordinated trip planning, consolidation of service offerings, and simplification of servce requests and payment have the potential to mitigate many barriers. Most of these systems are powered by human staff with varying degrees of software support. Humans involvement can be very powerful when selecting and coordinating services in complex scenarios, but it can limit impact due to challenges with scaling up custom, personalized service and with providing real-time service brokering. There also remain many policy-related challenges in all four functional areas, especially for paratransit and transportation network companies.

Promising technologies

- End-to-end multimodal trip planning has been deployed in some regions. Some systems support interregional trip planning.
- “One call” information centers support discovery of services and technologies.
- Integrated payment systems reduce confusion for people with cognitive or visual disabilities. Some smartcards can also be used for retail purchases.
- Flex-route transit has promise for reducing paratransit demand and improving travel by ATTRI stakeholders.
- Technology enhancements to fixed-route transit may relieve some of the demand.
- Dynamic scheduling, decision support, and dynamic monitoring have the potential to improve paratransit efficiency and service delivery.
- Transportation network companies (TNCs) offer increased transportation options to many ATTRI stakeholders. Some systems have specific features of direct benefit to those with certain disabilities. Likewise, cashless payment has high ease of use.
- Coordinated ride sharing for older adults has been successful in various parts of the country, including rural and suburban regions.
- Improved pedestrian infrastructure near bus stops by local municipalities can positively impact accessibility and use of fixed-route transit.

Technology gaps

- Many 511 options do not support the needs of ATTRI stakeholders as part of their mainstream services.
- Methods for service personalization based on end user needs are rare.
- Paratransit remains problematic for many reasons. Current implementations prohibit spontaneous travel, have poor scheduling, and are very expensive.
- Not enough taxi or TNC vehicles are wheelchair accessible.
- Some TNC drivers discriminate against people with disabilities even though TNC policies prohibit such behavior.
- It can be difficult to gather and maintain GIS data for pedestrian routes.

In short, there are many promising and successful technologies deployed in practice. Unfortunately, these are often restricted in use by policy and cost barriers. There also remain significant technology gaps that cannot be met with today’s products and systems.

Readers interested in learning about innovations and research activities are referred to the companion Innovation Scan **[INNO]** and Assessment of Relevant Research Scan **[ARR]**, respectively.

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