Accessible Transportation Technologies Research Initiative (ATTRI): Innovation Scan

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Innovation 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 an Innovation Scan [INNO], to survey 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 the segment of the test market user population or are based on reports by the organization that is introducing the technology.

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 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, innovations

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 an Innovation Scan [INNO], to survey 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 the segment of the test market user population or are based on reports by the organization that is introducing the technology.

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.

There are numerous promising innovations that may be leveraged towards the goals of the ATTRI program or used to inspire new functionality and methodologies during ATTRI system development and deployment. In this section we summarize some of these innovations. 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

- Most innovations in this technology category are designed to support people who are blind or low vision. There are numerous GPS-based devices and apps that support outdoor wayfinding and navigation by people in this group.
- There are innovative technologies for indoor use, but no single approach has emerged as the leading option. One of the reasons GPS is effective is that it serves a wide range of applications. This may be necessary for indoor approaches.
- Crowdsourcing has been utilized in this technology category, specifically in support of knowledge about transit vehicles and descriptions of pictures taken with smartphones.
- Intelligent software systems that tracks users and provides timely information and functionality are beginning to reach the market.
- While most mainstream smartphone apps for transit information are not accessible, some have included features valuable to people with certain disabilities. These include built-in ticketing, trip planning options for those with mobility disabilities, and service alerts.
- Head-up displays in passenger cars may help stakeholders with certain navigation tasks. This technology requires careful design and implementation to minimize distraction.
- New software has been developed to support rich descriptions of features along pedestrian routes. This includes accessibility-specific information, points of interest discovery, and coordinated community experiences.
- Bone conduction headphones are potentially valuable to users who wish to receive information yet not cover their ears, thereby restricting awareness of their surroundings.

ITS and Assistive Technologies

- There are many new, cost-affordable embedded computing options for prototyping novel devices, thus lowering the bar to implementation.
- Some local agencies have deployed metal tactile maps of train stations and local surroundings. Some of these include recorded audio notes.
- Simple, yet innovative transit fare gates designs have been tried in some regions. One is removing physical barriers in the gate’s path of travel. Another is support for remote station intervention (e.g., unlocking physical gates). These are similar to security badge pillars in the lobby of office buildings and remote door unlocking in multi-story residential buildings.
- Wheelchairs can now be secured in buses with an automated clamping arm.

- Neighborhood micro-cars designed for wheelchair users are entering the market. Likewise, prototypes for advanced neighborhood scooters have been demonstrated.
- At least one local municipality extends crosswalk timing when seniors and people with disabilities swipe their transit fare card at intersection pedestrian buttons.
- Some bicyclists record their commute and recreation rides using personal action cameras. This allows them to document hit-and-run collisions and other problems. This capability may be appealing to ATTRI stakeholders in similar scenarios.

Automation and Robotics

- Precision docking of buses makes it easier for many ATTRI stakeholders to board vehicles. On-vehicle video recording systems can enhance parking enforcement for bus lanes and pullouts.
- Robotic systems designed to support materials handling and transport might also be relevant for wheelchair and scooter stowage and retrieval at inter-city terminals.
- Drivable, video-based telepresence robots are becoming common and could be used to provide human assistance at low volume transit stations. However, many of these robots lack arms, thus limiting assistance tasks to informational and perceptual.
- It may be possible to mount a ramp to a hardened mobile robot for remote management and on-demand positioning of boarding ramps within stations.
- There have been efforts to develop long-range power wheelchairs for more convenient traversal of neighborhood distances. Similar to this are ultra small vehicles designed for the general public. Some of these blur the lines between cars, wheelchairs, and bicycles.
- Automated unmanned vehicles designed to shuttle pedestrians along pre-planned routes are slowly being deployed. Current versions travel at low speeds, thus lowering safety risk.
- Several companies are pursuing automated sidewalk assessment systems. These use robotic perception to characterize sidewalk quality and identify possible accessibility barriers.
- Lower body exoskeletons that allow walking over complex terrain have begun to enter the market. Most of these are currently limited to clinical applications but demonstrations have occurred in other settings.

Data Integration

- Participatory sensing and crowdsourcing can generate transportation data valuable to both travelers and service providers.
- Signal preemption systems are improving and may be safer for pedestrians.
- There have been successful demonstrations of wireless systems for vehicle-to-vehicle and vehicle-to-pedestrian warnings.
- Some transit apps integrate real-time arrival information with details about the local environment (e.g., bus stop features, pictures of station elevators, etc.).

- The layouts of interior spaces are being added to mainstream map software. This includes floor-level details for some buildings.
- Integrated information about multimodal transfers is being tested in some transit stations.
- Coordinated payment systems via smartcards and personal electronics are increasingly common. Riders are able to pay with phones and watches. Likewise, some transit smartcards are usable for retail and other purchases.
- Some high-end, heavily computerized cars support interaction through companion smartphone apps, thus supporting a variety of novel features.
- Smartphone integration with automotive secondary controls creates the possibility of having a consistent interface across multiple vehicles.
- Map developers are beginning to add pedestrian accessibility details to their data. Some of this is occurring directly in the map database while other features are added and stored in third-party apps.
- Advanced 311 reporting systems lower the effort needed to file a report, allow ticket tracking by the users, and support information for advocacy purposes.

Enhanced Human Service Transportation

- Service providers are leveraging modernization efforts towards computer-assisted coordination and information integration.
- Some countries are optimizing total cost to society using a systems-level view rather than containing transportation costs at the county or municipal level. For example, some health agencies cover various transportation costs as a means of lowering overall healthcare costs.
- New approaches are being developed and implemented for coordinated management of both expected and surprise events (e.g., disasters, large-scale sporting events, etc).
- Customer relationship management (CRM) tools have promise for delivery of personalized assistance in transportation systems, but the level of detail can be too poor for appropriate actions during travel. Likewise, it can be difficult for users to self-document their needs or even the fact that they have a disability.
- Caregiver tools for trip planning can limit exposure to undesirable events and barriers. Prototypes that alert caregivers when a person with a cognitive disability deviates from a trip plan have been deployed and tested.
- Transit agencies are beginning to view universal design as a method to address challenges created by an aging population and increased paratransit demand.
- Cross-zonal strategies for operating paratransit services are being tested.
- Novel bus service models are dynamically compiling user requests to establish virtual bus stops and coordinate demand for infrequent long haul trips.
- Transportation network companies (TNCs) are growing their ability to support the needs of ATTRI stakeholders and are introducing novel user interaction models that enhance accessibility.
- Cashless payment for taxis and TNCs can be implemented in ways that address ATTRI stakeholder needs.

- New carpool apps support discovery of possible drivers and have the potential to surface transportation alternatives for some ATTRI stakeholders.
- Transportation apps are increasingly displaying mode choice alternatives, with pricing and timing information.
- Innovations in community interaction tools via the web have created new ways for citizens to express their desires and needs to decision makers and each other.

Readers interested in learning about the state of the practice and research activities are referred to the companion State of the Practice **[SOP]** 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 emerging technologies and innovative methods with near-term potential. This document will identify potential benefits, use cases, obstacles, risks, and limitations of these technologies and methods to the ATTRI mission. It will also include implementations that are in limited public use but are not yet adopted on a large scale.

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 Innovation Scan

In the State of the Practice Scan **[SOP]**, we considered how ATTRI stakeholders can be uniquely challenged in each of the five technology areas: wayfinding and navigation, ITS and assistive technologies, automation and robotics, data integration, and enhanced human service transportation. While some solutions to those challenges may currently exist, greater mobility and independence for ATTRI stakeholders may be achieved through the deployment of innovative solutions. For example, ubiquitous wireless communications, personal devices, and online social communities have created a new technological ecosystem in which innovative applications are being developed and evaluated for ATTRI stakeholders.

This innovation scan identifies and explores deployments, demonstrations, emerging technologies, and innovative methods adopted by the transportation industry and perhaps other fields for addressing the needs of travelers with disabilities and for potentially improving mobility. Light rail, transit vehicles and transit systems, are part of the transportation field under consideration. The report focuses on innovative research that proposes the use of intelligent transportation systems (ITS), wireless communications, robotics, and artificial intelligence (AI). Within scope of the scan are: virtual caregivers and coaches; personal mobility devices; automated vehicles; real-time accessible traveler information and data needs; and scans of new technical solutions in other fields or industries. Technologies and methods listed in this scan are restricted to advances that are still being evaluated and that are expected to become market-ready in the next five years. This document also describes how these new innovations and strategies extend the range of existing transportation options. When necessary, the report identifies the potential implications, risks, limitations and obstacles to the adoption of such suggestions in terms of: stakeholders, technology, policy and institutions. As is true for many innovative products, some of the listed devices and systems may no longer be offered due to market forces or other barriers.

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, novel service models suitable for rural operations may be more appropriate for veterans since many reside in rural locations (Burkhardt, et al 2011).

3.1 Wayfinding and Navigation

In the State of the Practice **[SOP]** document, the discussion about wayfinding and navigation defined subprocesses involving: familiarization, localization and orientation, path planning, path traversal (locomotion), guidance, annotation, update and communication. The **[SOP]** document provides more detail for each subprocess, and each of the associated transportation challenges.

Innovations in wayfinding and navigation (WaN) technologies do not provide a comprehensive coverage of all of the processes that are identified in the **[SOP]** document, nor is there uniform coverage of WaN technologies for each of the ATTRI stakeholder categories. Innovations tend to be primarily oriented toward people who are blind or low vision and varied in their assumptions about target users and system architectures. Innovative WaN applications can be characterized as belonging to one of four types of system architectures for accumulating, presenting, and reasoning about WaN data. Each architecture type also determines the form factor of the device(s) involved as well as requirements for the amount of computational power and internet connectivity required. This section is organized, therefore, according to these four typical system architectures.

It is important to note that a system architecture defines how functionalities and capabilities of a system are implemented, not the functionalities and capabilities, themselves. The distinction is important because understanding how a system is constructed helps one understand how to choose the correct system architecture for one's needs and budget. Such understanding also helps anticipate costs and revisions to the system in the course of its lifecycle, as well as who will be responsible for which costs (Maier and Rechtin, 2013).

Transportation in the U.S. is architected as a system of systems (SOS) (Maier, 1999). If the scale of the SOS is very large, then it is considered an ultra-large-scale (ULS) system (Northrop, et al., 2006) in which the dominant components are humans and human institutions. For more on this topic, see Luzeaux, et al, (2013) and Jamshidi (2008).

The four architecture types used here to describe WaN innovations are:

- Infrastructure-Reliant WaN Architecture
- Crowdsourced WaN Architecture
- Independent WaN Architecture
- Socially-Aware WaN Architecture

Wayfinding and navigation innovations can be classified by the first three architecture types. The fourth architecture type represents a technology gap area for WaN and is included here to highlight alternative options. It is a result of software evolutions in service oriented architectures (SOAs), edge-enabled systems (EES), and autonomous systems.

Following descriptions of the architectures and examples of innovative applications, the four transportation challenge areas are discussed, followed by a summary of wayfinding and navigation gaps in innovation.

3.1.1 Infrastructure-Reliant WaN Architecture

The infrastructure-reliant wayfinding and navigation system architecture is where the WaN navigational guidance is provided by infrastructure that is external to the user's personal computing device. This often consists of computer servers that detail geolocation information combined with one or more GIS databases for streets, building floors and corridors, significant landmarks, and points of interest (POI). Database access is usually provided real-time via WiFi or internet connectivity, although some databases can be cached locally to the user's device. This use of server infrastructure external to the personal device allows the device to be as small in form as possible, not requiring much compute power, energy, and network connectivity. Most smartphone apps fall into this category.

3.1.1.1 GPS-based Apps for Outdoor WaN

The U.S.'s satellite-based Global Position Systems (GPS), an outdoor navigation service, provides the most common form of infrastructure-reliant wayfinding and navigation assistance. An article that provides a good overview of wayfinder GPS applications in addition to two applications, in particular, is Burton and Annis (2009). It evaluates accessible cell phone-based GPS navigation systems that can be used in conjunction with screen-reading software. The two apps that it considers are Wayfinder Access and Mobile Geo, providing a comparison of the two products' features and functions, as well as descriptions of the authors' experiences with Mobile Geo.

The following is a brief survey of some innovative technologies based on GPS infrastructure. They are all identified for people who are blind or low vision.

Trekker Breeze (2015) is a handheld talking GPS specifically designed for travelers who are blind or have low vision. The device provides step-by-step instructions for a route entered by the user. Trekker Breeze also verbally announces names of streets and intersections as the user passes by, whether they are walking or in a vehicle. Trekker Breeze also informs users of what points of interest, such as public services and businesses, are around them.

Another GPS device for blind and visually impaired travelers is Kapten Mobility (2015). Kapten Mobility is the size of a cell phone and has an accessible interface using voice recognition and can be worn on the neck or held in hand. It supports pedestrian and car navigation and also serves as an MP3 and audio book player. The user can interact with the device using voice to ask questions, perform certain actions or enter a destination address. The device allows the user to save points of interest and can announce these points of interest if the user is nearby.

There are several GPS applications (apps) available on iOS, Android, and Windows phones. Sendero GPS Lookaround (2015) is a free app available on iOS and Android devices designed for blind and visually impaired users. The app, coupled with the default VoiceOver for iOS and TalkBack for Android screen readers, announces current street, city, cross street, heading and the nearest 5 points of interest. The app does not provide routing, however, but it can also be used while GPS routing apps run in the background.

BlindSquare (2015) is an iOS app that is designed for blind and visually impaired travelers. Sourced from FourSquare and OpenStreetMap, the app describes the environment, announces points of interest, street intersections and user-defined POIs. BlindSquare's functions can be accessed through an audio menu. Similar to Lookaround, BlindSquare can be used in conjunction with third-party navigation apps for routing information. The app also has filters so that users can determine what information they want to hear and how often they want to hear it. Like Lookaround, BlindSquare requires VoiceOver to operate the app. However, BlindSquare also has a dedicated speech synthesizer available in different languages. A unique feature of this app is that it allows users to connect to social media (e.g. FourSquare, Facebook, Twitter, etc.).

VelaSense (2015) is an Android app that employs GPS for point-to-point navigation. Voice recognition is employed for issuing verbal commands. VelaSense uses the smartphone camera to locate and discern text, recognize objects whose images are stored in the device's database, and to navigate around obstacles or direct the user to street addresses. Planned future releases include a headset that will house gyroscopes and accelerometers to ascertain head position and movement in order to stabilize the image. Tiny vibrating motors will provide directional cues to the location of text, objects, and obstacles in front of the user. A microphone allows the user to deliver verbal commands to the device. An earpiece provides audio feedback of text, places or items that are important to the user.

The Seeing Eye GPS (2015) by Sendero Group is a free and fully accessible turn-by-turn GPS app available on iOS and Android. The app, also developed for blind and visually impaired travelers, has a simple menu on the lower portion of every screen consisting of route, points of interest (POI) and location. Two choices are available for POI data (i.e. Foursquare and TomTom). The app announces the street name and direction of travel at intersections. Furthermore, intersections are described with the clock face orientation of the streets. Directions are available for pedestrian and vehicle routes, with announcements for turns. The Seeing Eye GPS also features a "LookAround Wand" to hear nearby POI and intersections.

NAVIGON MobileNavigator, by Garmin (2015), is a mainstream navigation app available on iOS, Android and Windows Phone. NAVIGON is an app that serves as a fully functional mobile navigation system. It is not specifically designed for blind and visually impaired travelers but it can be accessed with VoiceOver on iOS, TalkBack on Android and Narrator on Windows Phone. NAVIGON has several country maps that can be purchased. The accessibility level of this app is unclear because it is not designed specifically for blind and visually impaired users.

MotionX-GPS (2015) is a mainstream navigation app available only on iOS. Its features include tracking outdoor activities, geocaching, sharing the coordinates of favorite locations, as well as allowing others to track your position in real-time. Similar to BlindSquare, users can interface with social media through the MotionX-GPS app. Again, the accessibility level of this app is unclear because it is not designed specifically for blind and visually impaired users.

Google Maps (2015) is another mainstream mapping service available on desktop and mobile devices (Android and iOS). While Google Maps provides online map services that enable route planning (e.g. vehicle, pedestrian, etc.), it does not provide continuous and dynamic information and notices that are often useful for blind and visually impaired travelers to accomplish safe and independent navigation. In addition, it does not allow users to verbally annotate their route. This is because Google Maps mainly targets sighted users. Google Maps is generally accessible through VoiceOver on iOS or TalkBack on Android.

3.1.1.2 Indoor Wayfinding and Navigation

No single indoor WaN technology serves as many stakeholders as GPS does for outdoor applications. Some technologies that are used for indoor navigation are: dead-reckoning, GPS (where the signal is still accessible), WiFi Received Signal Strength Indication (RSSI), Radio Frequency Identification (RFID), and Bluetooth beacons.

Dead-reckoning is a means of pose and localization orientation based on odometry and error correction via updates using landmarks. A landmark may be the last strong indoor GPS signal, a beacon, the recognition of indoor terrain features, or any signal that is strong-enough to detect and correct errors of estimation based on odometry up to that point. As the user travels between landmarks, dead-reckoning is used to keep track of distance and direction of travel. Navatar (Fallah, et al 2012) is an example of a smartphone application that uses the built-in features of a smartphone such as the accelerometer to perform dead-reckoning in between user-inputted landmarks.

For WiFi, a database of WiFi RSSI (signal strength) data is required for points on an indoor map. These points are given a WiFi fingerprint using the WiFi signals and their corresponding strengths. The user can be localized by matching a fingerprint of their location against a database of WiFi fingerprints associated with a map, as they travel through an indoor space (Quan, et al 2010). A major problem with using WiFi RSSI data is the inherent nature of these signals to fluctuate with time. Moreover, with the increased use of access points that adapt their signal strength according to the current load and interference caused by mobile phone WiFi radios, the challenge of using this technique for localization is worsened. To reduce the fluctuations, WiFi fingerprinting usually considers the dominant access points in an environment rather than all of the access points within range.

Some indoor WaN systems use Radio Frequency Identification (RFID) or Near Field Communication (NFC) tags, visible light communication, invisible light on either end of the visible light spectrum, and Bluetooth beacons (e.g., Ganz, et al 2012; Giudice, et al 2008), such as Apple's iBeacon protocol (Wikipedia, 2015). This requires installation of new infrastructure in a building. For example, RFID tags may be installed as localization landmarks throughout an indoor space. San Francisco International Airport has installed over 500 beacons and is exploring the effectiveness of a prototype system for people who are visually impaired (SFO, 2014).

The PERCEPT glove and kiosk is a proposed navigation system that relies on RFID technology to collect location information from the environment, and utilizing a routing server, calculates the shortest route from the user's current position to the destination (Ganz, et al 2012). To implement this proposal, RFID tags would have to be installed along a path within the building, which are then read and processed by the RFID reader embedded in the cane antenna. Though the underlying RFID technology is very mature and cost-effective, the need for additional RFID infrastructure is a potential limit to the scalability of the proposal. RFID methods have also been tested for people with cognitive disabilities (e.g., Chang, et al 2008).

Beacon based approaches have inly been deployed in limited applications (ClickAndGo, 2015), most likely because such technologies either require implementation of additional infrastructure or because the technology is deployed for a single use. In the case of infrastructure-based technologies, studies of additional uses of WaN indoor technologies by non-ATTRI stakeholders may provide insights and the stimulus of broader markets by which such technologies can become ubiquitous. The case of cost and limited functionality can be addressed by more research that is directed at these barriers to market entry. iBeacons and other low power Bluetooth beacon alternatives are marketed for sales and customer interaction applications, so there is potential to convene multiple product constituents towards wider deployments.

3.1.2 Crowdsourced WaN Architecture

A second form of WaN technology system architecture is one that uses information from crowdsourcing and geolocation infrastructure as a way of providing useful annotations on unambiguous, common or shared locations of reference. This architecture uses the same geolocation and georeferenced information as the infrastructure-reliant WaN architecture. The main difference is that the greatest source of GIS database annotations is from a population of users, or "the crowd", rather than from authoritative sources. The main drawback is that the trust and reliability of the annotations may be low at times, and if suitable policies are not in effect to limit misleading posts, good and reliable data can be overwhelmed and unretrievable due to vast amounts of unreliable data. The computation requirements for this type of WaN technology are often satisfied by the capabilities of smartphones, which are becoming increasingly common among ATTRI stakeholders. Due to the data intensive nature of crowdsourced approaches, technologies described in the Data Integration section below are also relevant. Infrastructure-reliant WaN architecture apps are increasingly adding crowdsourced enhancements to their GIS data.

Many systems do not allow users to specify their personal annotations, information and service needs, past experiences, and past successful trips, let alone find data sources that can respond to those needs. Such specific needs can vary widely in the ATTRI stakeholder community but may not be uncommon. We speculate that incentives and technologies can be implemented that support personalization through crowdsourcing, thus more responsive to the wide range of ATTRI stakeholder needs. Appropriate management techniques and crowd incentive structures are needed to maintain such systems (e.g., Tomasic, et al 2014). Our review of accessibility markup of online maps reveals most of products of this type run out of steam after a few months.

Another form of crowdsourcing is to provide help on demand, rather than attempt to markup an underlying data source. TapTapSee (2015) and VizWiz (2015) are free mobile camera apps available on iOS and Android. Designed specifically for blind and visually impaired users, these apps utilize the device’s camera to photograph and identify objects verbally within a usable time frame.

3.1.3 Independent WaN Architecture

The third form of innovative wayfinding and navigation technology is one in which the WaN logic is executed without input from crowds or external infrastructure. Due to considerations of power requirements and operating safety, these types of systems usually require more than one type of sensor to resolve systematic errors present in each individual sensor type. Reliable internet connectivity may or may not be needed. If a ubiquitous and reliable internet connection exists, then much of the computation can be offloaded to remote servers, and the on-person computing device can maintain a small and convenient profile. Without an internet connection, on-person computing can lead to larger device form factors. Advances in wearable computing can provide solutions to such challenges. Related robotics technology is discussed later in this document.

One example is Miniguide (2015), which is a handheld device that uses ultrasonic echo-location to detect objects. The device is intended to supplement information provided by a dog guide or a cane, rather than be used as a primary aid. The aid informs the user on the distance of an object – the faster the vibration, the closer the object. The device has an option to plug in headphones for audio feedback. According to cane and dog guide users, Miniguide can assist travelers who are blind or low vision in avoiding obstacles (e.g. parked cars, poles, street furniture), detecting overhanging obstacles (e.g. tree branches), navigating around objects (e.g. tables, chairs) and locating doorways, gaps, and determining if elevator doors are open. The buttons on the device are used to switch the device on or off and also to change settings, select modes and options. Miniguide is unable to detect drop offs like curbs, holes or platform edges.

3.1.4 Socially-Aware WaN Architecture

The socially-aware WaN technology architecture is a combination of the previously-described technologies designed to represent and integrate the needs of *the individual* with the services offered by *the ecosystem and community* of service providers. In this case, the “individual” can also be an autonomous software agent that acts on behalf of a human user. The agent proxy is “socially-aware” in the sense that it understands the infrastructure and application ecosystem in which it operates, and although it does not necessarily know which services it will use, it knows how to find them and utilize them.

Siri, Cortana, and other query-based interaction systems are precursor examples of this type of intelligent system. Google Now (2015) is another early example. This service autonomously identifies, retrieves, and surfaces information relevant to the user’s needs and current activities. Users select which “cards” to enable for specific functionality. Cards relevant to ATTRI stakeholders include options for requesting different on-demand car services, reserving Zipcar, context-sensitive transit information, and integration with the user’s calendar.

There are various forms of socially-aware application architectures (e.g., Sycara, et al. 2003; Sycara, et al. 2003b; Sullivan, 2007; Hall, et al., 2010). In some cases, the end user both produces and consumes software applications, thus assuming the amalgamated role of *prosumer*. The prosumer is as important as the software developer in adding to and maintaining the ecosystem. Given the wide-ranging and unique requirements of ATTRI stakeholders, this architecture model is likely to be relevant. Another possible method supports *ad hoc combination* of socially-aware services. We did not find any WaN technological innovations that can be cited as prototypical exemplars, so this relevant technology is discussed in the companion **[ARR]** document.

3.1.5 Transit

Innovative technologies that facilitate the use of transit systems concentrate mostly on familiarization, localization, orientation, location-aware information, 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 and safer.

Participants from a multimodal transit accessibility study (Jonnalagedda, et al 2014) reported using innovative technologies to pre-plan their routes (65% visual impairment, 33% mobility impairment). The technologies varied considerably by disability, but the most common are GPS and Google Maps. Those who used smartphones were heavily skewed towards iPhones. All of the participants who use smartphones reported using wayfinding and navigation technologies on their phone. The participants of this study only used wayfinding and navigation technologies for outdoor navigation. They were unaware of tools for indoor navigation, although they desired them.

Liu, et al. (2007) observed the living contexts of persons with visual disabilities, which also include indoor and outdoor wayfinding and navigation, and document challenges that can be addressed via smart assistive services.

Of the technologies in this classification that would target the ATTRI audience, most would be classified as belonging in this report due to their limited deployment to a small number of test markets. The following three sections highlight innovative technologies that provide assistance in three different forms: *audio assistance*, *trip planning*, *and real-time accessibility information*.

3.1.5.1 Audio Assistance

A very large gap exists in applications and assistance for persons with cognitive disabilities. One example of one such system is TravelMate (2015), a familiarization and end-to-end travel assistant for high functioning persons with cognitive disabilities. It has a wide range of customizable options that can be used for travel training. It supports crafting of end-to-end trips with instructions and landmark images. It also supports remote contact with caregivers. There is anecdotal evidence that TravelMate is also helpful to those without disabilities who are unfamiliar with the local area (DeLoatche, 2015).

Narrative maps typically provide verbal or text-based descriptions of an area to the user. The Directions app is an example of a smartphone application narrative map. Directions functions both indoors and outdoors and also allows the visually impaired user to receive instructions from a sighted user (Sheepy and Salenikovich, 2013). Likewise, ClickAndGo Wayfinding Maps (2015) offers a form of narrative map (verbal or text-based descriptions of an area) that functions both indoors and outdoors. ClickAndGo is a website that uses pre-recorded instructions from landmark to landmark that can be downloaded as audio or braille text. The company is also starting to deploy wireless beacon systems in certain locations.

The Kapten PLUS Personal Navigation Device (2015; Shaver, 2011) is a small GPS locator designed to be carried on one's person. As the user walks down the street, the device speaks direction and location, so the user always knows where they are and where they're heading. In addition, the user can plan and store routes and tag locations for later reference (Shaver, 2011).

3.1.5.2 Trip Planning

Some trip planners utilize transit data regarding elevators and other station details. An example was the wheelchair accessible route option for New York City available in Hopstop (2015). This option was an exception rather than the rule as many apps lack this feature and few transit agencies provide open data feeds for elevators and other accessibility features. Unfortunately, many apps and smartphone friendly websites are not accessible, including those developed by transit agencies (NCAM, 2012).

The Wisetrip (2015) projects, which were funded under the Sixth and Seventh Framework Programmes by the European Commission, focused specifically on next generation multimodal trip planners. Areas of attention included incorporation of traveler preferences and needs, multi-criteria trip planning, trip replanning, real-time data management, alerts, carbon footprint calculations, integrated ticketing, and user interaction through mobile internet devices. While most of the participating trip planners are focused on transit, some also include intercity options like air travel and ferries. 9292 (2015), the participating trip planner from the Netherlands, includes an interesting advanced option. A checkbox is provided for people who want to incorporate 5 minutes of extra time during transfers. This is a very convenient option for people who have trouble moving through transit stations quickly.

Automated call systems are often disliked due to their confusing, constrained decision tree architectures. Evidence suggests people prefer “chat” style interactions for transit information (Yoo et al., 2010). To this end, the Let’s Go! system provides trip planning and transit information using computer understanding through natural spoken dialog. As of 2010, the project had served over 130K calls over a five-year window (Black et al., 2011; Let’s Go!, 2012; DialRC, 2012). The usability of such systems for people with speech, hearing, and communications impediments needs to be studied.

Integration of points of interest (POI) and caregiver tools are also important. These are discussed in later sections.

3.1.5.3 Real-Time Accessibility Information

As transit agencies increase the number of open data feeds for third party developers, new opportunities exist for innovative ways to provide real-time accessibility information to riders while they are executing their trip. For example, the Roll with Me (2015) and Wheely (2015) apps provide real-time accessibility information for Chicago and New York City transit, respectively (Swartz, 2014). These apps provide a variety of transit functions but are highlighted here for their out-of-service alerts for elevators.

In some cities real-time transit data is not available or does not include key information. To address this gap, some teams utilize a crowdsourcing model to populate accessibility information. For example, the Tiramisu Transit app asks riders to document how full buses are using rating levels which align with the likelihood of obtaining a seat or there being enough room for a wheelchair to board (Steinfeld, et al 2012). Early interviews with riders with disabilities revealed fullness as an important piece of information while traveling as it helps riders determine if they need to adjust their route or take alternate forms of transportation. The crowdsourcing approach has been successful with over 180,000 contributions within the Pittsburgh region since the summer of 2011.

3.1.6 Personal Vehicles

Head-up displays (HUDs) have the potential to enhance in-vehicle navigation for a variety of reasons, especially for older drivers due to the extra time needed to refocus when switching between the windshield and the dashboard (Steinfeld, 2008). While speech-based guidance also eliminates the need to look at the dashboard, it can be problematic for people with hearing loss. Some companies have brought HUDs for navigation to the market, including Garmin HUD (2015).

There are technical and human factors concerns when implementing head-up displays. The former is why most systems are small and show only one or two colors. The "Keeping Eyes on the Road: The Promise of Voice Controls and Head-Up Displays Workshop" at the Transportation Research Board 2015 Annual Meeting examined the use of head-up displays, virtual reality (VR) integration, and speech technologies OEMs design into vehicles to enhance driver's perception and control (virtual visual pillars, highlighting roadway, pedestrian detection, obstacle proximity detection, speech-enabled commands, different forms of human-machine-interface to control and navigate vehicle). Consensus opinions from attendees were (1) very careful studies and evaluations must be performed to ensure that the systems do not impair driver performance or unduly distract them and (2) "after market" devices, such as those introduced by PDAs and smartphones, are tremendous risks because they are not designed to minimize distractions to the drivers, nor are they likely to be subject to evaluations. This aligns with decades of automotive research on head-up displays. Therefore, input or product review from a driver rehabilitation therapist is likely an important step prior to use.

3.1.7 First / Last Mile

One of the complicated tasks of wayfinding and trip planning is linking transit routes with accessible paths along the "first / last mile," or to and from a person's origin and destination. There are some examples of systems that integrate the two during trip planning or allow users to explore pedestrian routes using accessibility filters. For example, Karimi & Zimmerman (2013) have deployed a website that allows people to explore accessible trips around the University of Pittsburgh using bus and pedestrian routes. The system embeds pedestrian details with local shuttle bus information, incorporates user capabilities into trip plans (e.g., no steep hills for manual wheelchair users, etc). This level of coverage is not simple since it usually requires manual markup of all sidewalks, ramps, doors, and other features.

Two applications from Google's NianticLabs are interesting and possibly relevant to ATTRI stakeholders. Field Trip (2015) is a local point of interest (POI) discovery app designed to help people find interesting things to see and do in their immediate vicinity. One can imagine similar functionality for exploring good first / last mile routes to discover places to rest or seek shelter from weather. Ingress (2015) is an augmented reality game where teams compete for territory while moving around the real world. The app is inherently graphic but may have some useful user experience and interaction concepts relevant to local navigation and interaction between co-located users.

3.1.8 Pedestrian

Current technology navigation systems for sighted users typically choose the shortest path to a destination. This may not be ideal when the user who has a visual disability, however. For example, the shortest path to a point may have higher probability of the traveler veering away from the planned path, whereas a path that goes along walls will be longer but more reliably help them maintain direction and orientation (Fallaha, et al. 2013).

Directions should include personal and sometimes ephemeral landmarks that can be sensed during navigation by the user while remaining simple and effective. The navigation system should also take into consideration all the environmental information utilized by the user to orient themselves. Any change to an environment may confuse a person with a visual or cognitive disability because some of the landmarks and clues they have used for wayfinding may have been altered or lost. For example, the smell of coffee at a particular place in a building may be a clue to identify the location of a coffee shop. If that coffee shop is re-located or is converted into another type of store, the traveler may not recognize the location. Although this environmental change may not pose a problem for a navigation system, this becomes a relevant change to communicate to the user. Therefore, navigation systems for people with visual or cognitive disability should incorporate accessible environmental landmarks and clues into their instruction sets, and notify users of relevant changes to the environment as needed. Sometimes, these sensory landmarks can be generated by the transportation system itself. For example, trains in Lausanne, Switzerland play meaningful sounds within the passenger cabin as they enter certain stations (e.g., water sounds at a station next to a well known fountain).

Bluetooth location beacons, often called iBeacons, are increasingly being deployed for marketing and other reasons. Some teams are exploring how to leverage these beacons for use by people with disabilities in transportation settings like airports, buildings, and transit terminals (ATMac, 2014; ClickAndGo, 2015). iBeacons are an improvement over RFID-based wayfinding approaches tested in the past (e.g., Mau, et al 2008) as they have a larger range and integrate more smoothly with smartphone apps. By using Bluetooth, it is no longer necessary for the user to swipe a sensor in close proximity to a wall-mounted electronic tag. This also enables sensory landmarkmarks on the user's personal electronics.

Most people prefer discrete, yet accessible information displays. For example, people who are blind or low vision will often utilize earbuds instead of speakers. However, users do not want information to limit their interaction with the environment and ability to pay attention to environmental cues. To allay some of these concerns, assistive navigation devices must allow the users who are blind or low vision to listen to the device through at most one ear and easily vary the verbosity of the instructions based on the situation. Bone conduction headphones are an innovative approach to mitigating this problem since they do not cover the user’s ears.

Navigating intersections is also a concern for many ATTRI stakeholders. Under a Phase I SBIR, a team from CLR Analytics is exploring the use of real-time data from local signal controllers or Traffic Management Center (TMC) to provide information and alerts regarding signal timing to cyclists and pedestrians with disabilities in a variety of formats. An Android prototype, which was designed using input from potential users, was developed and demonstrated. The app determines the phone’s location and orientation, interprets the user’s state (approaching, waiting at, or crossing an intersection), and issues the preferred alerts alerts as needed.

Apple Maps (2015) is the default mapping application for iOS devices. Similar to Google Maps, Apple Maps mainly targets sighted users. However, with VoiceOver, users who are blind or low vision can activate the app’s tracking feature by double tapping the *Tracking* toggle on the lower left corner of the screen (Davert, 2014). Tracking alerts the user when approaching an intersection, announces cross streets, and notifies the user of points of interest.

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 areas. The broad range of wireless and sensor-based communications and information technology employed in Intelligent Transportation Systems (ITS), combined with a number of other assistive technologies can create new innovative accessible transportation solutions. This will include the traditional accessible, assistive, and adaptive devices that currently help with daily living activities and 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 the Internet of Things (IoT) being applied to wearable technology such as wristbands, glasses, clothing or others. These technologies will also integrate with vehicles, infrastructure, and pedestrians using 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 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.

A technology development that has potential for significant innovation in the ITS and assistive technology domains across all modes of transportation is the proliferation of new platforms for embedded systems. In the past, developers were often required to design and fabricate custom boards and computer circuits for embedded systems. The market has seen recent introductions of new computing platforms that support low-cost ITS and assistive technologies, like Arduino, Raspberry Pi, and even smartphone-variant systems (e.g., Android). Manufacturers have also accelerated the deployment of useful elements in embedded systems, rapid prototyping tools like 3D printing at home, sewable electronics, and open source software and hardware. As a result of these new options, technology innovators can jump directly to prototyping and possibly implementation without significant up-front investments in embedded hardware, especially for small market niche products. As a result, there will likely be new innovations in this space of direct use to ATTRI stakeholders.

3.2.1 Transit

While printed maps of transit stations are common in most places, tactile maps at appropriate heights are not. When found, these are typically made out of metal and designed for both sighted and blind users. Some deployments include innovative features like integrated audio recordings (e.g., Tokyo suburbs) and multiple languages.

One location where the latter can be experienced is in the Seoul Metro, which has also employed interesting fare gate designs. The first type are fare gates with no physical barrier in the path of travel. Riders pay at the gate and move between waist-high pillars as usual but do not have to wait for doors or push through turnstiles. Wheelchair accessible gates are wider and off to the side so users can line up on the gate easily. The lack of physical barriers makes sense in high volume locations since losses due to fare jumping are likely overshadowed by the increased throughput. Older fare gates in Seoul are of the traditional style, but also include interesting assistive technology. Wheelchair accessible gates include help buttons and two-way call options for remote station agent intervention. This improves convenience for people with disabilities and extends the number of entrances an agent can support. These are similar to security badge pillars in the lobby office buildings and remote door unlocking in multi-story residential buildings, respectively.

Another area where assistive technology innovation is occurring is in wheelchair securement. Examples include the DOR and Quantum products from Q'Straint (2015). The former is designed for personal vehicles but has potential for smaller transit vehicles. It supports roll-in securement with no added components on the wheelchair. The latter is designed for rear-facing securement in larger public transit buses. After a user rolls into the spot, automated arms rotate down and press against the sides of the wheelchair. Securement can occur in less than 25 seconds, dramatically faster than manual approaches, and does not require assistance from the driver.

3.2.2 Personal Vehicles

In addition to the Q'Straint DOR (2015), other innovations have been developed in the personal vehicle market. These generally center around entry and egress from vehicles for both seniors and people with disabilities. For example, the Freedom Seat by Freedom Sciences (2015) swings out of the car door and adjusts height for easy transfer from a wheelchair, walker, or cane. The motorized seat then moves back into a regular position.

Several companies have designed small cars specifically designed for use by people in wheelchairs. Examples include Kenguru (2015) and Quovis (2015). These vehicles are single occupant vehicles where the driver stays in their wheelchair and enters using an integrated ramp. Their small size also allows for easier maneuverability and less space in a parking spot, which can be important when trying to position for entry and egress.

3.2.3 First / Last Mile

Many scooters and power wheelchairs move much faster than normal walking speeds. There have been efforts to design platforms which can travel significantly faster and longer, thus allowing users to cover longer distances conveniently. This, of course, requires attention to device range and stability. Two examples are the POSCO smart chair (2012) and the Suzuki Mio (2006). Similar systems designed for use by a wider population are listed in later sections of this report.

Safe navigation of crosswalks can be a key challenge for people who need more time to traverse an intersection. If there is no safe island zone mid-intersection then signal light duration becomes very important. The Singapore Land Transport Authority (LTA) started Green Man Plus, an innovative approach to address this challenge, in 2009 and is in the process of expanding coverage to almost 500 crossings by the end of 2015 (Silverberg, 2014). Seniors and people with disabilities swipe their transit fare card at the intersection pedestrian buttons. This adds time for crossing and is accompanied by feedback so users know their card was accepted.

3.2.4 Pedestrian

A team from Microsoft and the charity Guide Dogs demonstrated a system designed to support independent pedestrian travel by people who are blind (Warnick, 2014). Like similar approaches, this system used a combination of smartphone GPS and Bluetooth beacons to help provide route guidance and point of interest (POI) details. As mentioned earlier, this project focused on interaction through bone-conducting headphones. By focusing on bone-conduction, the team was able to bypass the inherent problem of masking the user's hearing with headphones while still providing stereo content. The team also involved partners from the neighboring area, including transit providers, local companies and government entities, and the local supermarket. The information interaction model incorporated both push and pull features, thus allowing the system to provide ad hoc value.

One trend among cyclists may be applicable for ATTRI populations who feel routinely at risk when crossing streets. Some cyclists are now wearing sports cameras (e.g., GoPro) which save video in a loop, similar to dashboard or body cameras. This helps them identify cars when involved in hit-and-run collisions or to collect evidence in the case of a crash. This capability may be appealing for others who are regularly threatened by roadway vehicles.

3.3 Automation and Robotics

Automated vehicles and robotics are expected to improve mobility for those unable or unwilling to drive and enhance independent and spontaneous travel capabilities for travelers with disabilities. One area of particular interest is exploring the use of vehicle automation to solve first / last mile mobility issues, thereby 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 their travel and hence improve personal mobility across the transportation network. This section also includes advances in computer vision, artificial intelligence, assistive robots (potentially partially humanized), and facial recognition software that could address a variety of travel related issues for ATTRI stakeholders. Some of these systems could be used to create virtual caregivers / concierge services and other such applications to guide travelers and assist decisionmaking.

3.3.1 Transit

3.3.1.1 Docking

Tight docking of buses to curbs at bus stops supports easier boarding for people with disabilities and seniors who need low step thresholds. A major barrier to a bus driver’s ability to pull up to the curb is whether there are cars illegally parked in the bus stop areas. In some cities this is common enough to warrant aggressive enforcement but good coverage can be difficult to achieve. To address this challenge and illegal use of dedicated transit lanes, the city of San Francisco has equipped all MUNI buses with cameras for automated enforcement (Bialick, 2015).

3.3.1.2 Assistance in Stations and Terminals

Due to new advances in technology, there are a number of new robotics solutions in the manufacturing domain (e.g., Seegrid, 2015; Rethink Robotics, 2015). Due to new techniques which support working in close proximity to humans, some of these have possible applications in the ATTRI domain. For example, there are new systems designed to support materials handling and transport which might also be relevant for wheelchair and scooter stowage and retrieval at inter-city terminals. Robot forklift technology could also be adapted to replace human moved and articulated wheelchair lifts. Some robots already support being taught by humans and are low-cost enough to support experimentation (Rethink Robotics, 2015), thus opening the door to off the shelf and novel applications by non-roboticists. Research examples in this area are in the **[ARR]** document.

There has also been a proliferation of drivable, video-based telepresence robots. Systems of this type are becoming increasingly common in hospital environments as a mechanism for enabling expert consultations. These robots could be used to provide human assistance at low volume transit stations. However, many of these robots lack arms thus limiting assistance tasks to informational and perceptual.

One area robotics has in common with transportation are challenges associated with grade changes. Some robots handle this through shape reconfiguration and creative mechanisms. Some of these robots could be adapted to support varying grade changes for vehicles, which is common, for example, in rail systems that utilize adaptive, heterogeneous vehicles. Likewise, it would be straightforward to mount a ramp to a hardened robot (e.g., iRobot, 2015) for remote management and on-demand positioning of boarding ramps within stations. Again, this would support accessibility at stations where assigning human staff may not be cost effective.

3.3.2 Personal Vehicles

As mentioned earlier, there have been efforts to develop long-range power wheelchairs for more convenient traversal of neighborhood distances. Similar to this are ultra small vehicles designed for the general public. Some of these blur the lines between cars and wheelchairs or bicycles.

The Segway is a well known vehicle of this type and it is used by some people in the ATTRI stakeholder population, but it lacks certain safety features needed for operation in mixed traffic. The Segway P.U.M.A. (Personal Urban Mobility & Accessibility; Segway, 2015) and GM ENV (Snyder, 2014) attempt to address this issue by increasing the size of the platform, adding seats, and incorporating car-like features for safety and operation. Some versions of the GM ENV have also been automated for demonstrations (Walker, 2013). The main problems with many of these vehicles are the clearances and postures needed to enter or exit the vehicles, which are likely to be very difficult for most ATTRI stakeholders.

At the other extreme are the Airwheel (2015) unicycle and board platforms and the Honda UNI-Cub β (Honda, 2013). These compact platforms are designed to be brought into buildings, sometimes folded into sizes comparable to briefcases, are highly maneuverable (e.g., Dillard, 2014), and are likely to mix better with pedestrian traffic on sidewalks than a Segway. The size and maneuverability may be undesirable for some ATTRI stakeholders due to the need for good balance and the risk of falls. They may be very attractive, however, to younger stakeholders who are not allowed to drive on streets but have the physical ability to manage these vehicles. Also note that some of these vehicles allow the user to sit down, thus lowering physical effort in comparison to a Segway.

In between these two extremes are the Toyota i-Unit (2004), i-Real (2007; Pollard, 2007; Wilson, 2007), and i-Road (Wood, 2013) concept vehicles. This series of vehicles has progressed from a modernistic wheelchair design which altered posture based on speed, to a three-wheeled high-speed wheelchair variation, to an enclosed leaning road vehicle. The latter is close to a BMW C-1 motorcycle (Motavalli, 2009) in spirit but with easier entry and exit due to the door design and low seat height. While gaining street legal status, the i-Road sacrifices the i-Real’s ability to move through buildings and pedestrian spaces. For those who prefer something closer to an electric bicycle, Drymer (2015) makes electric assist tilting tricyles.

3.3.3 First / Last Mile

Automated unmanned vehicles designed to traverse routes used by pedestrians are very common in controlled locations (e.g., materials handling in factories, express courier sorting facilities, hospital pharmacy, food and linen services) and are entering use in certain military contexts, especially for outdoor patrols (e.g., Cheng, 2014). In these contexts, the likelihood of collisions with humans is either low or considered an acceptable risk.

In the transportation space, the Induct NAVYA (2015; Del-Colle, 2014; formerly named Navia) shuttle addresses this risk by traveling at speeds below 12.5 mph and by using laser sensors. The low speeds are reasonable for those who cannot walk far distances. The system is designed to travel along a preprogrammed route, rather than a network or local neighborhood, so utility is limited to areas where there is enough demand along a corridor. Field tests are underway in Europe. Research efforts in this space, like CityMobil2 and ARIBO, are discussed in the **[ARR]** document.

These types of systems are worth examining in contrast with manually driven car sharing models. For example, Nissan has deployed the two-seat, fully electric Hypermini in both Japan (Teramoto, et al 2000; Teramoto, 2015) and the United States (Brayer & Fracfort, 2006). Findings from the latter suggest this type of car is more useful for car sharing models than neighborhood electric vehicles which have a top speed of 25 mph and are usually limited to roads with speed limits under 35 mph. This makes sense for trips in suburban or rural areas due to the likelihood of higher speed roads. In Japan, the Hyperminis configured for car sharing were tested in several locations, including a transit station. User satisfaction was high and the vehicles were used extensively for first / last mile commutes.

3.3.4 Pedestrian

One of the big challenges in pedestrian travel is for a user to know which sidewalk routes are problematic or in a bad state of repair before committing to using them. As mentioned in the **[SOP]** document, there are manual approaches to collecting data and some people use Google StreetView to scout ahead. Unfortunately, StreetView cannot provide overhead views and most satellite map views lack adequate resolution to assess possible routes. Aerial drones are possibly relevant for capturing such data but are not currently used.

To address this challenge, several companies are pursuing automated sidewalk assessment systems. Three example systems are the Starodub ULIP (2015), Beneficial Designs PROWAP (2015), and PATHVU PathMeT (2015). All three require human action to travel along the sidewalk but each system uses robotic sensing to profile the sidewalk and identify potential barriers to safe pedestrian travel. The former is mounted on a Segway while the latter two are modified carts.

In terms of assistance during travel, there have been efforts to develop robotic systems to assist pedestrian motion, but the most advanced of these are a few niche products in the assisted walker domain. These have had limited impact and market life due to high cost and an emphasis on indoor mobility.

Recent focus has been on lower body exoskeletons that allow walking over complex terrain. The ReWalk system (2015) is on the market while other systems, like Indego (2015), Rex (2015), and Ekso (2015), are in the pipeline. A key challenge in reaching the market appears to be FDA approval (Chen, 2012; Tita, 2014). Technical concerns include battery range, interactions with the built environment, and whether a user can easily board or egress a vehicle.

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: 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. In addition, a traveler can provide his or her specific information to build a standardized user profile for a person with accessibility needs that allows for location based services both locally and nationally. Based on the user profile, applications can be developed to alert relevant authorities in advance of a user’s trip requiring special accommodations, such as a wheelchair at the airport.

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.

Innovation in information apps and servers depends, to a large degree, on advances in data integration technologies. While much can be gained by open data and data description standards, the real technological gap is in the way in which arbitrary data descriptions can be published, thus making it difficult to integrate data sources. Please see the discussion on Data Integration in the **[ARR]** for more detail on research efforts to support the integration of data for new and novel applications.

3.4.1 Cross-Cutting

3.4.1.1 Participatory Sensing

A popular method for collecting large quantities of data is to enlist the help of the general public through participatory sensing methods. There is a long tradition of this model in certain communities, like citizen weather stations, but this approach has only recently entered the transportation domain.

Waze is the most successful example of this type of crowdsourcing. It was initially developed to better characterize the road network within Israel, but subsequently grew rapidly to other parts of the world. The popularity of the system stems from inferences about congestion, congestion-sensitive navigation guidance, reporting of details about roadway incidents, and identification of speed traps. Waze is now sharing their data with certain municipalities to improve Traffic Management Center (TMC) operations. Some of the Waze features are directly relevant to ATTRI stakeholders. For example, the crowdsourced incident details can provide insight to drivers who are deaf or hard of hearing. Mainstream sources, like radio traffic reports, are typically only in audio form.

Other useful data that can be crowdsourced are the locations where there are typically dense concentrations of pedestrians. This could be obtained through mobile phone locations or camera based sensors (e.g., Hsu, 2014). This kind of data has the potential to be very useful when planning routes, either for drivers or pedestrians. For example, it may be desirable to route drivers with reduced capability away from such areas in order to reduce risk exposure. Likewise, people who want the option to request help from others may prefer routes that are more populated. Tracking pedestrians at this scale, especially with data that could lead to identification, would likely require embedded privacy protections.

The Tiramisu Transit system uses participatory sensing to collect real-time data about bus location and fullness. Users can also submit qualitative data as notes. Privacy is managed by making data contributions opt-in, rather than opt-out. This allows the user to control when they are being tracked. This approach is still effective at gathering good quantitative and qualitative data but care should be taken when selecting motivational approaches (Steinfeld, et al 2012; Steinfeld, et al 2014; Tomasic, et al 2014; Tomasic, et al 2015).

3.4.1.2 Wireless Technologies

Signal preemption, where transit or emergency vehicles request favorable changes in signal light timing, is well established and heavily used. Traditional methods employ local vehicle-to-infrastructure communications using short range wireless or infrared technologies. An alternative technique feeds the vehicle's reported location from GPS into a traffic control system which subsequently controls nearby signal lights. This has the benefit of knowing in which branch of an intersection a vehicle is located without the line of sight limitations of infrared. However, GPS methods can be problematic if vehicle location cannot be discerned due to GPS dropouts. This can be resolved with systems that merge GPS and local communications (e.g., Opticom, 2015). The added robustness of this approach increases safety for pedestrians at the intersection, especially for those who move slowly or have trouble perceiving sirens, since signals are more likely to change well in advance of the vehicle's arrival, thereby eliminating the case where emergency vehicles are forced to avoid pedestrians.

Discussion of Dedicated Short Range Communications (DSRC) is located in the **[ARR]** document but teams have explored similar concepts using off the shelf technology. One particularly innovative idea is to use WiFi to broadcast WiFi device location and motion to fellow devices. In this approach, devices can compare their relative motions with details shared by nearby WiFi devices and determine if a collision is imminent. Most smartphones have WiFi and it would not be a major leap to implement this kind of WiFi beacon in vehicles (no Internet is needed). Example implementations of this model include vehicle-to-vehicle (Misener, et al 2005) and vehicle-to-pedestrian (Dhondge, et al 2014; Lewin, 2014) collision warnings. The latter introduced the idea of altering information in the WiFi hotspot labelling protocol, thus allowing a decentralized approach and avoiding the need to actually establish a WiFi connection. The important information is visible when scanning for nearby hotspots. This increases speed and reliability.

3.4.2 Transit

Real-time arrival systems have significant value to all riders, including ATTRI stakeholders, and there is a need for integration of point of interest (POI) details for better trip planning. Examples and discussion of these types of information are in the **[SOP]**. An innovative approach towards integrating such information is exemplified by Wheely (2015), a transit and pedestrian wayfinding and POI app that includes photographs of elevator locations. This is a step beyond simply allowing access to Google StreetView since it eliminates the often difficult task of finding the elevator entrance in random street scenes. Likewise, the OneBusAway app is now integrating crowdsourced details about individual bus stops (OneBusAway, 2015; Kennedy, 2014), thus helping people who are blind to better understand what roadside infrastructure is present at their local stop.

An increasing number of indoor spaces are now visible in Google Maps, with POI and building details for each floor embedded in maps (e.g., Grand Central in New York). This has significant potential for app developers in that multi-floor navigation may become easier to accomplish for popular buildings. This would allow routes within large, complex stations to be planned for users based on capabilities and preferences.

Japan Railways East has been exploring how integrated data can benefit their riders, especially with the Tokyo 2020 Olympics only a few years away. Example concepts being field tested include augmented reality using smartphones and optical tags, video projections of station maps on floors, multilingual route finders, in-train travel apps, navigation using Bluetooth beacons, and digital watermarks on signs so users can acquire language translations easily (Ishizuka, 2014). Another project, in conjunction with the University of Tokyo, explored how integration of bus information with train arrival times in a smartphone app helped riders with multimodal transfers (Hidaka & Suda, 2014). Riders found this integration to be helpful. It is realistic to believe integrated information about multimodal transfers would also be valuable for ATTRI stakeholders due to the potential need for more time or station agent help during transfers (e.g., manual lifts at rail platforms).

Countries in Asia have also been at the forefront of innovative fare payment models. Payment via near field communication (NFC) in phones has been possible for some time now, but this is now being extended. For example, the T-Money system in Seoul can be used at a variety of purchase points, like taxi cabs, convenience stores, etc. Scaled down versions of this functionality are also present at some university campuses in the United States. Being able to travel and purchase items with only a smartphone, NFC equipped smartwatches (e.g. Apple Watch), or smartcards, can have significant value to ATTRI stakeholders due to reduced cognitive load when managing multiple accounts and easy identification of what card (if any) is used to pay. In some cases, the onboard security of a device may also help protect against theft and unauthorized use.

3.4.3 Personal Vehicles

Some high-end, heavily computerized cars support interaction through companion smartphone apps (e.g., Tesla, 2015; BMW, 2015). Example features include the ability to unlock or lock the car remotely, honk the horn or flash the lights, manage battery charging (for electric vehicles), and vent the car of hot air. Remote starting and door control has been around a long time, especially in the modified vehicle market. The new feature relevant to ATTRI stakeholders is the opportunity to access the vehicle through the internet. This means users are not restricted to the range of a standard RF transmitter. In addition, some apps can show the location of the car on a map, further helping those who need help with memory or navigation. Remote control over the interior climate of the car is also useful for those susceptible to extreme heat or cold. Some companies are either testing or deploying companion apps for smartwatches too (e.g., Collie, 2015; Moren, 2015), which may be useful for those who want to keep their phone in a more secure or weatherproof location.

One of the biggest challenges for drivers when switching to an unfamiliar car is managing secondary controls, like radio, in-vehicle navigation, etc. Both Apple and Google have been advancing their respective automotive integration user interfaces (Apple, 2015; Android, 2015). These systems, especially Apple Car Play, take over the car's multifunction dashboard screen and provide a consistent user interface for smartphone functions. This should help reduce cognitive load when driving an unfamiliar car and may help those who could benefit from consistent user interfaces in both their phone and car. As with all driver-vehicle interaction systems, there is a risk of increased distraction if apps are not carefully designed and evaluated for the driving environment.

3.4.4 First / Last Mile

OpenStreetMap introduced the ability to add wheelchair accessibility markup into the map database. Unfortunately, coverage is somewhat limited and new data is slow to be added. Such data has value when implementing pedestrian route plans, especially to and from transit stops. This can also be used to more easily assess whether a person with a disability can safely reach a fixed-route stop for particular locations, thereby allowing determination of whether paratransit should be provided. There is room for innovation on gathering accessibility data through other sources for better coverage within map databases like OpenStreetMap or as layers within Google Maps.

3.4.5 Pedestrian

Every few years a new crowdsource system for marking up accessibility barriers around cities is developed and deployed. Systems of this type pre-date smartphones; precursor versions used multimedia messaging service (MMS) for contributing observations, although the technology continues to evolve (e.g., GENEVE*accessible, 2008; Wheelmap, 2015). The basic premise of such systems is attractive since crowdsourcing has the potential to generate a lot of useful accessibility data. As discussed in (Steinfeld, et al., 2010), the core problem with many of these systems is the "black hole" effect where users receive no feedback on whether a problem is being resolved, or even if the responsible party is aware of the complaint. For example, indicating a store is not accessible due to a step entrance has no impact if nobody from the store or building gets the complaint. Value to the user is low since rarely do their contributions result in any action, thus reducing the likelihood of continued reporting. If the developer cannot increase value to the user in some form, the app community typically disintegrates within 18 months.

Newer, more advanced 311 systems are now being deployed in some cities that manage the reporting problem better. These systems lower the effort needed to file a report, allow ticket tracking by the users, and support information for advocacy purposes.

Feedback and accountability is present, as compared to unofficial crowdsourced systems, so the value to the user is higher. NYC 311 (2015) is an example of innovative data integration and resources for local residents since the site and smartphone app includes both the ability to file and track complaints, but also obtain useful information and alerts for daily life. However, there is still room for improvement as 311 systems have limited effectiveness for non-governmental entities. Also, most 311 systems do not reveal individual complaints to those who did not make them, thus limiting the ability to find accessibility complaints made by others.

3.5 Enhanced Human Service Transportation

The focus of this 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 are linking paratransit, demand-response transportation, and fixed-route transit in order to increase flexibility and options of travelers with disabilities.

3.5.1 Cross-Cutting

3.5.1.1 Centralized Coordination

One of the major advances in human service transportation has been modernization to electronic dispatch and case management. Information integration across various service providers, either in the form of shared data or resources, has led to a number of projects seeking to leverage modernization towards computer-assisted coordination.

In the United States this effort has been led by the Mobility Services for All Americans (MSAA; 2015) program. This program focuses on creating Travel Management Coordination Centers (TMCCs) for centralized management of service delivery, payment, traveler information, and computer supported demand-response trips. Evaluation of deployment sites revealed significant advances across many important metrics. Examples from (MSAA, 2015) include, but are not limited to:

- *Increased staff productivity;*
- *Integrated point of access for traveler support;*
- *Improved fleet scheduling, dispatching, and routing;*
- *Streamlined reporting, billing, and financial transactions;*
- *Simplified fare payment, collection, and processing;*
- *Enhanced traveler information and travel management capability with accessibility features; and*

- *Ability to address last-minute requests and cancellations without significant effort or inefficiencies.*

In Europe, the focus has been on identification and dissemination of best practices and coordinated management of unusual events. To promote best practices, the MEDIATE and ACCESS 2 ALL (European Commission, 2012; European Commission, 2013) programs developed and disseminated frameworks and detailed recommendations for more accessible transportation. The project, ACCESS 2 ALL included 290 recommendations on policy, standardization, human-machine interaction, and specific services, including some pertaining to technology. One important nuance in some European countries is that sometimes different top-level government entities are responsible for different types of travel. For example, some health agencies cover various transportation costs as a means of lowering overall healthcare costs. These countries are optimizing total cost to society using a systems-level view rather than containing transportation costs at the county or municipal level. In the United States, the Veterans Administration uses over the road buses to help veterans get to distant VA sites when needed. This is similar, but at a different scale.

Unusual transportation operations are range from expected to surprises. The far end of the spectrum is large, long lead time events like the Olympics and FIFA World Cup. The STADIUM (2015) project analyzed service delivery and transportation management for such events and developed a decision support system for planners of new events. The decision support system has a strong emphasis on ITS applications, especially in areas of traveler information, fare payment, traffic management, and service provider coordination. Worth noting is the recommendation that host entities should focus on enhancing existing transportation and information systems rather than wholesale replacement. This makes sense since the installed systems will be in place long after the large event and the needs and desires that motivated the existing systems will be what matters when the event is over. The project final report also accurately notes that services added for the event, like those for people with disabilities, provide the opportunity for post-event service enhancement (Tomassini, 2013).

Work has also been done to address unexpected distruptions. The SAVE ME (2015) project explored solutions for coordinated evacuation management for various transportation venues. It included specific attention to identifying and maintaining status updates on people with disabilities using coordinated software tools and mobile devices. Demonstrations in physical simulated tests (i.e., mock disasters) showed significantly faster evacuations of people with disabilities. One aspect of the SAVE ME demonstration system that has direct value to everyday travel was the inclusion of a traveler profile which included details about the user's abilities. This allowed appropriate service delivery during the demonstration.

Customer relationship management (CRM) tools are used throughout society and in many transportation settings. However, they often lack adequate support for detailed information about traveler capabilities or needs. For example, an airline ticket system may let travelers or agents flag a ticket as belonging to a person with a disability, but the level of detail is often too poor for appropriate actions during travel. For example, a traveler who is deaf or hard of hearing cannot indicate they lipread and speak, rather than sign. Likewise, a review of multiple United States airline websites revealed no easy method for users to self-document their needs or even the fact that they have a disability. Handling of wheelchairs and scooters is also routinely problematic and inefficient in both air and train travel due to the reactive response to wheelchair or scooter users, rather than being ready with the right equipment at the right time in the right place. Therefore, there is significant opportunity for transportation service providers to leverage modern CRM tools and case-based reasoning software to improve delivery of service through more descriptive preferences, computer-generated guidance to agents and staff through database driven alerts, and dynamic tracking of resources and customers while in the system to pre-position resources and prevent or mitigate service breakdowns. These kinds of advanced techniques are easily feasible with modern day technology.

3.5.1.2 Caregiver Tools

The challenges caregivers face are similar to those of service providers, but their needs are more specific and personal. Prior to departure, good trip planning tools can limit exposure to undesirable events and barriers. Some approaches were explicitly designed for people with disabilities. For example, the Travel Assistance Device (TAD) tested in Tampa, Florida directly supports riders with cognitive disabilities (Barbeau et al., 2010; Winters et al., 2010). A key feature of the Travel Assistance Device is the ability for caregivers to program routes via websites for riders with disabilities. Users receive prompts regarding which bus to board, when to get off, and caregivers receive route deviation alerts, if necessary. Other teams have also explored approaches that support overall system navigation for riders with cognitive disabilities (Repenning and Ioannidou, 2006).

3.5.2 Transit

Transit agencies are beginning to view universal design as a method to address challenges created by an aging population and increased paratransit demand. To this end, they are utilizing educational resources to help advance their practices (e.g., Easter Seals, 2009; APTA, 2011). Similar dissemination and policy efforts have occurred through the UNIACCESS project (European Commission, 2010). This multi-country effort led to a series of policy recommendations centered on non-discrimination, accessibility certification, and standardization.

Within the paratransit domain, Quadrifoglio (2013) examined and quantified the inefficiencies caused by policies in Los Angeles County that limit the pickup of paratransit passengers in zones other than that in which the trip originated. This creates a dependence of the passenger on at least two different providers for one round-trip service. For the service provider this results in less ride-sharing, an increase in the number of empty miles driven, and as much as a 30% cost increase for Paratransit services. This Transit Cooperative Research Program (TCRP) project explored innovative cross-zonal strategies for operating paratransit services, quantifying the effects of the strategies in the following terms: (1) reduction in the number of empty miles driven, (2) reduction in operating costs for the paratransit provider, based on the number of vehicles used and number of miles driven, (3) the number of passenger trips per revenue hour, as a measure of company productivity, and (4) improvement in the level of service for the customer. Both static and dynamic scheduling strategies were considered and have promise for deployment. Validation experiments were conducted in Boston, Houston and Los Angeles.

In parallel to policy changes in how traditional agencies support ATTRI stakeholders, several novel private transit models have emerged in the United States by leveraging social computing models. The first is Bridj (2015), which uses market demand within two neighborhoods to dynamically identify and generate virtual bus stops for service between the two areas. Riders indicate their location and travel desires through a smartphone app, which also provides details on stops and routes. Small transit vehicles are dispatched using optimization techniques. Service animals are always permitted and Bridj asks people with disabilities to contact customer service in advance. This is partly due to the vehicles used for service, which are provided through local subcontractors. Discussions with Bridj reveal an interest in more accessible vehicle designs but challenges in implementation during this early stage in the company's existence. Bridj is interesting from an ATTRI perspective since their model naturally finds and fills gaps within existing transit systems and supports spontaneous travel. As such, this model may be able to reduce pressure on paratransit demand and reduce first / last mile distances. Virtual bus stops also allow for adjustments when local traffic and infrastructure create barriers. Since there is no fixed roadside infrastructure, it is possible to shift the stop to a more usable location.

Skedaddle (2015) is similar to Bridj but focused on the longer, charter trip market. Once 15 riders have committed to a trip, the bus is scheduled. The service requires reservations multiple days in advance but may be useful for supporting less regular, longer routes for communities that can make such plans. For example, Skedaddle may be attractive for veterans, military families, and seniors since origins and destinations from suburban and rural bases or senior communities become more cost effective than taxis or transportation network companies (TNCs) like Uber and Lyft.

3.5.3 Taxis and Shared Vehicles

During the course of this work, the team reached out to representatives at both Uber and Lyft to get insight on how TNC services interact with people with disabilities. 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 is currently piloting service models designed for accessibility in multiple cities, including larger ones like New York and Chicago, with the plan to develop data-driven best practices for this model. In Chicago, San Diego, and Houston, Uber is testing a pilot called UberASSIST where top drivers receive additional training developed in partnership with groups like the Open Doors Organization. This training includes core topics in disability terminology, legislation, methods of assisting specific disability groups, and technical aspects of assistance. This includes training on transfers and wheelchair breakdowns. This sort of specialized training within the larger Uber driver pool is in line with requests from disability rights groups. Lyft has similar pilots underway.

An interesting system designed for people who are visually impaired has been implemented for taxi networks in cities such as Boston and New York (Quinn, 2012). The taxis in these cities feature screens in the backseat that generally play commercials and allow for credit-card payment. For visually impaired travelers, however, the screen can be activated to become an audio system by swiping a special card. The audio system updates the traveler on the status of the meter, eliminating the need for total trust in the fare declared by the driver at the end. The system also assists in the payment process, allowing visually impaired users to pay independently using a credit card. Distribution of the activation cards to visually impaired travelers is the main challenge, though. Many cards are distributed through rehabilitation centers for the visually impaired, but travelers who are not affiliated may not have access to information about the system nor to a card. Furthermore, the system lacks an orientation aspect, since it does not announce the street or avenue that is being passed by the taxi, which could be useful information for the visually impaired traveler as well.

3.5.4 Personal Vehicles

Drivers who are willing to carpool, use transportation network companies (TNCs), bike share, or take transit can now use smartphone apps to better manage their trips. Examples include Commuter Connections, Carma, and RideScout. Commuter Connections (2015) makes it easier to directly identify and coordinate free carpools. Commuters can search for carpool partners by entering their home and work locations and work hours and receive contact information for commuters with similar schedules. Information on the location of park-and-ride lots where commuters can meet carpools or vanpools is also provided. The app even allows access to the guaranteed ride-home program as well as carpool rewards. Carma (2015) is similar but is designed for drivers to receive distance based payment from the passenger. Drivers can also designate passengers who can ride with them for free. While most of the Carma cities are major urban areas, the service is also deployed in smaller cities (e.g., Cork, Ireland). Both of these systems are useful for ATTRI populations who are having difficulty finding good carpool options. Commuter Connections' guaranteed ride home feature is also important for those who lack the financial resources to switch to a taxi or TNC when a carpool plan unexpectedly fails.

RideScout (2015), which was founded by two veterans, aggregates multiple ground transportation options, allowing users to compare travel times and costs in real time. The app integrates transit information, carsharing, bikesharing, taxis, and peer-to-peer ridesharing based on user specified origins and destinations. Google Maps also allows easy comparisons of several mode options. This level of integration is useful for ATTRI stakeholders who have difficulty integrating information across disparate sources, especially when spontaneous trips are needed.

3.5.5 First / Last Mile & Pedestrian

Innovations in community interaction tools via the web have created new ways for citizens to express their desires and needs to decision makers and each other. Municipalities and third party developers have started using social computing to gather data and increase citizen engagement. The OpenPlan Shareabouts (2015) platform is a good example of participatory urban planning using online maps and discussions. The platform is embedded within a specific planning campaign website and has been used to inform the design of bike sharing services (e.g., New York, Portland, Cincinnati, etc), and problematic phone booths (New York). The Shareabout deployment that is most relevant to ATTRI stakeholders is the one that documents dangerous intersections in Brooklyn.

There are also third-party services designed for 311-style reporting. For example, SeeClickFix (2015) and FixMyStreet by mySociety (2015) act as front ends for civic engagement about streets, sidewalks, and other issues. SeeClickFix offers tools that allow municipal agencies to integrate the app with their reporting systems for routing to the responsible department. FixMyStreet is designed to be a standalone platform for municipalities. Since the code is open source, it is conceivable that interested parties could adapt it for ATTRI specific concepts.

4 Conclusions

There are numerous promising innovations that may be leveraged towards the goals of the ATTRI program or used to inspire new functionality and methodologies during ATTRI system development and deployment. In this section, we summarize some of these innovations. 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

As with the State of the Practice **[SOP]**, most innovations in this technology category center on the visual functional area. Some aspects of these systems are also relevant to the cognition functional area since guided routing can lower cognitive load and mitigate complexity. The most promising innovations in this space leverage location-aware, real-time information feeds to remove uncertainty and mitigate confusion while traveling. Errors and unexpected events while traveling can impact ATTRI stakeholders more than other users. A persistent problem within this technology sector is that many mainstream apps and internet-based services contain accessibility barriers. This is most pronounced in the vision and cognition functional areas.

- There are numerous GPS-based devices and apps that support outdoor wayfinding and navigation by people who are blind or low vision.
- There are innovative technologies for indoor use, but no single approach has emerged as the leading option. One of the reasons GPS is effective is that it serves a wide range of applications. This may be necessary for indoor approaches.
- Crowdsourcing has been utilized in this technology category, specifically in support of knowledge about transit vehicles and descriptions of pictures taken with smartphones.
- Intelligent software systems that tracks users and provides timely information and functionality are beginning to reach the market.
- While most mainstream smartphone apps for transit information are not accessible, some have included features valuable to people with certain disabilities. These include built-in ticketing, trip planning options for those with mobility disabilities, and service alerts.
- Head-up displays in passenger cars may help stakeholders with certain navigation tasks. This technology requires careful design and implementation to minimize distraction.

- New software has been developed to support rich descriptions of features along pedestrian routes. This includes accessibility-specific information, points of interest discovery, and coordinated community experiences.
- Bone conduction headphones are potentially valuable to users who wish to receive information yet not cover their ears, thereby restricting awareness of their surroundings.

ITS and Assistive Technologies

New technologies are enabling novel approaches to some long-standing barriers in the mobility functional area. Better fare systems permit removal of physical gates at train stations, automated wheelchair securement systems are now on the market, and vehicles specifically designed for wheelchair users are being manufactured. Some of these are enabled by advances in the same low-cost technologies powering the Internet of Things. It is reasonable to expect more innovations of this type due to the widespread availability of low-cost, internet-equipped, small-sized computing platforms. Similarly, advances in small batch and on-demand manufacturing allow companies to bring more niche products to market. Again, this will enable new innovations that were previously cost-prohibitive.

- There are many new, cost-affordable embedded computing options for prototyping novel devices, thus lowering the bar to implementation.
- Some local agencies have deployed metal tactile maps of train stations and local surroundings. Some of these include recorded audio notes.
- Simple, yet innovative transit fare gates designs have been tried in some regions. One is removing physical barriers in the gate’s path of travel. Another is support for remote station intervention (e.g., unlocking physical gates). These are similar to security badge pillars in the lobby of office buildings and remote door unlocking in multi-story residential buildings.
- Wheelchairs can now be secured in buses with an automated clamping arm.
- Neighborhood micro-cars designed for wheelchair users are entering the market. Likewise, prototypes for advanced neighborhood scooters have been demonstrated.
- At least one local municipality extends crosswalk timing when seniors and people with disabilities swipe their transit fare card at intersection pedestrian buttons.
- Some bicyclists record their commute and recreation rides using personal action cameras. This allows them to document hit-and-run collisions and other problems. This capability may be appealing to ATTRI stakeholders in similar scenarios.

Automation and Robotics

Robots are becoming increasingly capable and cost effective in relevant markets, such as manufacturing, materials handling, and telepresence. Some of these innovations have the potential to significiantly impact the mobility functional area, but also have value to the other three areas. For example, a telepresence robot is very useful for someone with a high spinal cord injury, but could also be effective for someone with cognitive disabilities who cannot currently travel independently. Some advances in robotics within defense and manufacturing may be applicable in assistive technology applications that require high power and durability.

Also, the State of the Practice **[SOP]** identified the need for autonomy for first / last mile vehicles. Innovations to address this are beginning to enter the market.

- Precision docking of buses makes it easier for many ATTRI stakeholders to board vehicles. On-vehicle video recording systems can enhance parking enforcement for bus lanes and pullouts.
- Robotic systems designed to support materials handling and transport might also be relevant for wheelchair and scooter stowage and retrieval at inter-city terminals.
- Drivable, video-based telepresence robots are becoming common and could be used to provide human assistance at low volume transit stations. However, many of these robots lack arms, thus limiting assistance tasks to informational and perceptual.
- It may be possible to mount a ramp to a hardened mobile robot for remote management and on-demand positioning of boarding ramps within stations.
- There have been efforts to develop long-range power wheelchairs for more convenient traversal of neighborhood distances. Similar to this are ultra small vehicles designed for the general public. Some of these blur the lines between cars, wheelchairs, and bicycles.
- Automated unmanned vehicles designed to shuttle pedestrians along pre-planned routes are slowly being deployed. Current versions travel at low speeds, thus lowering safety risk.
- Several companies are pursuing automated sidewalk assessment systems. These use robotic perception to characterize sidewalk quality and identify possible accessibility barriers.
- Lower body exoskeletons that allow walking over complex terrain have begun to enter the market. Most of these are currently limited to clinical applications but demonstrations have occurred in other settings.

Data Integration

There have been many innovations demonstrating the power of data integration. Advances have come in a variety of forms, such as crowdsourcing, peer-to-peer communication, and coordination across databases and systems. For example, multiple personal vehicle manufacturers now offer remote management of cars from smartphone apps and even watches. Connected vehicle methods for vehicle-to-pedestrian warnings have been demonstrated. Payment can now be done by smartphone or watches, thereby removing the need to manage a smartcard balance or find a smartcard in a bag or pocket. These types of innovations support advances in all four functional areas. This technology area is advancing faster than the other areas, mostly due to the fact than novel products and systems can be developed and deployed without the addition of new, specialized hardware. There are also large market forces driving demand for more integration (e.g., more efficient system operations, user profiling by companies and advertisers, etc) and advances in enabling consumer hardware components (e.g., smartphones, wearable electronics, etc).

- Participatory sensing and crowdsourcing can generate transportation data valuable to both travelers and service providers.

- Signal preemption systems are improving and may be safer for pedestrians.
- There have been successful demonstrations of wireless systems for vehicle-to-vehicle and vehicle-to-pedestrian warnings.
- Some transit apps integrate real-time arrival information with details about the local environment (e.g., bus stop features, pictures of station elevators, etc.).
- The layouts of interior spaces are being added to mainstream map software. This includes floor-level details for some buildings.
- Integrated information about multimodal transfers is being tested in some transit stations.
- Coordinated payment systems via smartcards and personal electronics are increasingly common. Riders are able to pay with phones and watches. Likewise, some transit smartcards are usable for retail and other purchases.
- Some high-end, heavily computerized cars support interaction through companion smartphone apps, thus supporting a variety of novel features.
- Smartphone integration with automotive secondary controls creates the possibility of having a consistent interface across multiple vehicles.
- Map developers are beginning to add pedestrian accessibility details to their data. Some of this is occurring directly in the map database while other features are added and stored in third-party apps.
- Advanced 311 reporting systems lower the effort needed to file a report, allow ticket tracking by the users, and support information for advocacy purposes.

Enhanced Human Service Transportation

Advances in data integration are enabling a new class of innovative service products and systems. First, data integration permits a systems-level perspective for cost management, which in turn, reveals new service opportunities and new ways of justifying service changes. Second, better data systems support innovations in service quality by surfacing more information to service providers and opportunities for tailored experiences. Third, new sources of data are enabling novel service offerings by transit and paratransit systems. Since many of these innovations are at the service level, all four functional areas are experiencing accessibility advances in transportation. In parallel with this data revolution, transportation network companies continue to be a disruptive influence. This occurs both through new modes of travel but also as a market force on established service providers, thereby spurring innovation in both sectors of the industry.

- Service providers are leveraging modernization efforts towards computer-assisted coordination and information integration.
- Some countries are optimizing total cost to society using a systems-level view rather than containing transportation costs at the county or municipal level. For example, some health agencies cover various transportation costs as a means of lowering overall healthcare costs.
- New approaches are being developed and implemented for coordinated management of both expected and surprise events (e.g., disasters, large-scale sporting events, etc).

- Customer relationship management (CRM) tools have promise for delivery of personalized assistance in transportation systems, but the level of detail can be too poor for appropriate actions during travel. Likewise, it can be difficult for users to self-document their needs or even the fact that they have a disability.
- Caregiver tools for trip planning can limit exposure to undesirable events and barriers. Prototypes that alert caregivers when a person with a cognitive disability deviates from a trip plan have been deployed and tested.
- Transit agencies are beginning to view universal design as a method to address challenges created by an aging population and increased paratransit demand.
- Cross-zonal strategies for operating paratransit services are being tested.
- Novel bus service models are dynamically compiling user requests to establish virtual bus stops and coordinate demand for infrequent long haul trips.
- Transportation network companies (TNCs) are growing their ability to support the needs of ATTRI stakeholders and are introducing novel user interaction models that enhance accessibility.
- Cashless payment for taxis and TNCs can be implemented in ways that address ATTRI stakeholder needs.
- New carpool apps support discovery of possible drivers and have the potential to surface transportation alternatives for some ATTRI stakeholders.
- Transportation apps are increasingly displaying mode choice alternatives, with pricing and timing information.
- Innovations in community interaction tools via the web have created new ways for citizens to express their desires and needs to decision makers and each other.

Just as low-cost computing changed white-collar work and personal entertainment, computation is rapidly bringing innovation to accessible transportation. It can be challenging for traditional service providers to find and evaluate such innovations due to the pace of change. Likewise, policies have not always kept pace with innovation.

Readers interested in learning about the state of the practice and research activities are referred to the companion State of the Practice **[SOP]** and Assessment of Relevant Research Scan **[ARR]**, respectively.

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