Accessible Transportation Technologies Research Initiative (ATTRI): Assessment of Relevant Research

Joseph Andrew Giampapa, Aaron Steinfeld, Ermine Teves,
M. Bernardine Dias, Zachary Rubinstein

CMU-RI-TR-17-17

The Robotics Institute
Carnegie Mellon University
Pittsburgh, Pennsylvania 15213

April, 2017

Accessible Transportation Technologies Research Initiative (ATTRI)

Assessment of Relevant Research

Final Report — April 10, 2017
CMU-RI-TR-17-17

Joseph Andrew Giampapa, Aaron Steinfeld, Ermine Teves,
M. Bernardine Dias, Zachary Rubinstein

Robotics Institute, Carnegie Mellon University

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 Assessment of Relevant Research [ARR], to report on research technologies - both within and outside of the transportation domain - that show promise at addressing 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 public experiences with such technologies in the transportation context.

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

Keywords: Accessible transportation, technology, community travel, international scan, research

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.

This effort was funded by Federal Highway Administration (FHWA), and conducted in partnership via an Interagency Agreement (IAA number ED-OSE-14-K-0005) with the National Institute on Disability, Independent Living, and Rehabilitation Research (NIDILRR).

iii. Table of Contents

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

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.

1 Executive Summary**Error! Reference source not found.**

Utilizing the latest ATTRI program roadmap, this document also includes recommendations of technologies and research collaboration opportunities for ATTRI to pursue in Phase 2 of the program. These can be summarized as:

Recommendations for Wayfinding and Navigation

- **Integration of Map Data from Various Sources.** Aside from regular digital map data, relevant information includes methods for easily integrating location-specific data from other sources, like reading the location of a bus stop and which routes arrive there from an external GTFS source. Since these maps are likely to be used by many, they should be accessible for third party developers via open data and open services models. There already exist large, rich mapping efforts within industry so building the underlying digital map data is likely to be inefficient. Instead, efforts should be focused on how to make these maps better and more useful to the ATTRI developer community. Research is needed on how to bridge gaps between different map databases for easier and better integration. For example, one map database may assign a precise GPS descriptor for a bus stop while a different database may just say curb cuts are present at an intersection.
- **Infrastructure Descriptions.** While there are many methods for documenting building structures and features, there are some infrastructure elements which have a strong impact on ATTRI stakeholders that need standardized encoding methods. For example, teams are gathering data on the presence of stairs or the quality of sidewalks but lack standardized descriptions for sharing with others. Inconsistencies make scalable, nationwide products difficult to achieve.
- **ATTRI Specific Data.** While there is a lot of useful data in existing map systems, they often lack critical data relevant to ATTRI stakeholders. For example, a Points of Interest database may give the location of a store, but not where the entry door is, whether there are steps at the door, or if a restaurant has an accessible bathroom. It is possible to look for this in tools like StreetView or to call the store phone number, but this information is not machine-readable, so it is hard for navigation tools to know these details.
- **Universal Indoor Localization.** While there has been regular and steady improvement in low cost localization in GPS-denied regions, advances in wayfinding and navigation continue to be constrained by technology and institutional barriers. Infrastructure based approaches (e.g., Bluetooth beacons) will likely require a universal design approach due to deployment costs and other barriers. Likewise, good localization is valuable to people with varying disabilities so a universal approach will lower barriers for multiple user groups.
- **Accessible Personal Interfaces.** New ATTRI applications developed for smartphones and wearable electronics need to be accessible. Ideally, these applications will embody universal design principles to enable broader use.

Recommendations for ITS and Assistive Technologies

- **Modernized Maintenance and Asset Management.** Applying ITS approaches to assistive technology maintenance and asset management is a rich area for advancement. For example, real-time information about vehicle lift or elevator state of repair should be easily shared with transit information apps.
- **Remote assistance.** Economic pressures on transportation providers create problems in cases where local staffing is not economically feasible. This goes beyond simple voice calls and includes the ability of remote service providers to actuate local assistive technologies and infrastructure. At the simplest level, transit agency staff should be able to control specific fare gates, doors, and elevators remotely so ATTRI stakeholders do not have to wait for service. Advanced remote assistance, like moving a robotic ramp or lift into place for grade changes between platforms and trains, should also be considered.
- **Barrier Traversal.** Better assistive technology for managing curbs and sidewalk barriers are often necessary. Grade change barriers impact access to many places of employment, retail, and residences are present due to cost of modification and other reasons. The Veterans Administration has made progress on these issues through novel wheelchair designs, so this may be an opportunity for collaboration. Robot movement over poor terrain is also a topic that is heavily researched by the Department of Defense. Similar systems could also be used to facilitate snow and ice removal, when necessary.

Recommendations for Automation and Robotics

- **Shared Neighborhood Autonomous Vehicles.** The efforts of ARIBO and CityMobil2 are an excellent start but more research in this space is needed due to the size and severity of the first / last mile problem within the United States. Vehicles of this type have significant promise in resolving first / last mile access to employment and residences, so more research on this topic is needed. In particular, solutions that do not require a driver’s license for operation are necessary.
- **Accessible Vehicles.** Unfortunately, most vehicles on the road are not inherently accessible. This limits the ability for one to independently board autonomous vehicles or ride in transportation network company (TNC) or taxi vehicles. Seamless vehicle boarding and egress is necessary to fully realize the potential of these services. Car sharing service models, electric vehicles, and autonomous vehicles create opportunities for novel vehicle design. Advances on this issue will be especially important for access to healthcare and employment in areas not well served by transit or pedestrian alternatives. The ability to enter a passenger vehicle from a suburban or rural location is also important for people aging in place.

- **Look Ahead Functions.** Navigation and routing that do not predict upcoming changes in the environment will inherently produce reactive behaviors. A system that does not infer how the user and other parties move and act will inadvertently create problems. Users do not want to be led into dangerous areas or be perceived as rude by bystanders. Prediction also enables more appropriate infrastructure decision-making, better autonomy, and overall safety. Research is needed on how to provide this kind of forward looking, socially aware guidance.

Recommendations for Data Integration

- **Open Data and Open Services.** Continuing the trend of open data provided by municipal services and information sources will be important for scaling ATTRI solutions across the country. Open services, where code and data is private but usable by third parties through easily coded software tools (e.g., Google Maps API), will also be important for accelerating development of novel ATTRI systems. This recommendation aligns with Smart Cities efforts and Internet of Things applications, thus illustrating the importance of coordination on standards with related efforts.
- **Connectivity.** Early research on wireless connectivity between ATTRI stakeholders and other transportation elements has demonstrated safety and convenience. Continued effort is needed in this area, especially for applications for personal connectivity. Functionality like alerting for pedestrian-vehicle collsions and relaying information about bus route numbers can be more effective and timely with connectivity. Universal design is important due to market forces and deployment barriers. Therefore, systems should utilize mainstream connectivity methods.
- **Machine Readable Personal Profiles.** Since ATTRI stakeholders have significant variability in needs and capabilities, it will be important to encode individual preferences on how service and technology should be used. For example, a scooter user may be willing and able to walk out of a train or airplane to meet their scooter at the platform or gate. Requiring them to wait for a transfer chair or lift that is 20 minutes away is counterproductive. Likewise, some databases merely indicate the traveler is disabled, rather than specific needs, thereby leading to provision of the wrong service or technology. In some cases, these profiles could be learned from direct interaction with the user or caregiver. The location and access to these profiles is an open question but it will be necessary to preserve privacy so profiles are not used improperly.
- **Service Matchmaking.** Some ATTRI stakeholders have access to services limited to their population group (e.g., senior discounts, military transportation, etc). In other cases, caregivers may wish to limit which transportation services are offered as a means of reducing complexity or exposure to danger. Automated methods for filtering, identifying, and surfacing the right transportation options to users will be important. This includes the option to do hypothetical planning since

awareness and easy utilization of transportation services can positively impact employment opportunities and access to healthcare.

- **Community Generated Data.** Existing research has shown that members of the community, including those who are not ATTRI stakeholders, are more than willing to provide knowledge and expertise in transportation systems. Research has also shown such contributions can be very effective in bridging accessibility gaps. Unfortunately, many crowdsource systems fail over time for a variety of reasons, thus suggesting that new models for generalizable approaches are needed. Research is needed on how to motivate and sustain these communities as well as how to use such contributions to better support independent travel by ATTRI stakeholders.

Recommendations for Enhanced Human Service Transportation

- **TNCs and Ridesharing.** Initiatives by TNCs to involve ATTRI stakeholders are an opportunity to better understand how accessible versions of these services can positively impact travel independence. Research on existing programs like UberMILITARY and the use of accessible vehicles by TNCs are opportunities to obtain rapid insight on these trends. Likewise, many government agencies are interested in how to ensure equal access for people with disabilities within these service models. TNCs are also an attractive employment option for ATTRI stakeholders. Due to all of these questions, there is a need to better understand how TNCs and ridsharing technologies can transport and employ ATTRI stakeholders.
- **Mode Shifting.** The increasing numbers of older adults and the long-term focus on suburban planning within the United States will be increasingly problematic as older adults transition out of driving. Neighborhood automated vehicles and private on-demand ride services may help mitigate this looming problem, but it will also be important to support and encourage shifts to non-driving modes. This will likely require a variety of technologies and services designed to coach users through unfamiliar transportation systems, inform users of options in easy to understand ways, and act as a trusted friend in order to detect and warn users when they are about to make a mistake (e.g., take an outbound train instead of an inbound one). Caregiver tools for remote support are also relevant.

Specific products identified in the recommendations or in the document are not endorsments. 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.

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, crowdsourced information, and accessibility data. Five (5) technology areas have emerged as ATTRI focus areas: *wayfinding and navigation*, *ITS and 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 an overview of innovations, technologies, and research that are applicable to the ATTRI vision.

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

Another emphasis of this document will be on travel in modes other than personal vehicles. This is due to the high percentage of non-drivers in the ATTRI target populations. The exception to this will be the sections that forecast the use of autonomous vehicles by the target populations. An assessment of the potential impact of autonomous vehicles on such populations will be made, as well. 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.

Finally, universal design with technology focused solutions is increasingly viewed as an important method of implementing cost-effective and broadly valuable accessible solutions. As such, this document will include observations on how certain solutions have broad appeal and impact beyond the ATTRI target populations.

The assessment will include recommendations on, "key collaborative opportunities with national and international efforts on emerging technologies relative to accessible transportation" (IAA, Task 4).

This will include documentation of current research projects that have the potential for collaboration and partnering opportunities in later ATTRI program activities, with details on how relevant research projects fit into the latest ATTRI program roadmap (supplied from FHWA program officer).

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 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 Technology Research Areas**, 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 application 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 Assessment of Relevant Research

This report provides an assessment of research that is relevant to accessible transportation and technologies, with recommendations of key collaborative opportunities with national and international efforts. This document includes the following criteria in its assessments: focus of study, methods used, findings, relevance to the ATTRI vision and purpose, and implications to the stakeholders of development and deployment of such research. This report focuses on relevant research that proposes the use of intelligent transportation systems (ITS), wireless communications, robotics, and artificial intelligence (AI).

The report also identifies and discusses potential collaboration and partnering opportunities that can be leveraged in forthcoming ATTRI program activities. Utilizing the latest ATTRI FHWA program roadmap, this document includes recommendations of technologies and research collaboration opportunities for ATTRI to pursue in Phase 2 of the program. This is documented at the end of the document in the section labeled Recommendations for Phase 2 Utilization.

3.1 Wayfinding and Navigation

Readers of the companion reports will recall that wayfinding and navigation processes include: familiarization, localization and orientation, path planning, path traversal (locomotion), guidance, annotation, update and communication. We have also included a section on indoor maps since research in this space is important for the other parts of WaN. The **[SOP]** document provides more detail for each subprocess, and each of the associated transportation challenges. The **[INNO]** document describes technology innovations, classified according to their systems architecture, along with gaps in the domain.

Technologies found for WaN are typically for people with visual or cognitive disabilities, but many have broader value to people without disabilities. For example, WaN can be challenging for those new to a locale or unfamiliar with riding urban transit. There is significantly more work in research for persons with visual disabilities, so we organize that research according to the WaN process areas. Research of relevance to persons with cognitive disabilities does not offer as many assistive options. With the exception of a research group that performed studies on WaN familiarization aids for persons with cognitive disabilities, the other type of research that we found related to evaluating specific technological interfaces: (Liu, et al, 2008; Chang, et al., 2008; Liu, et al., 2009).

3.1.1 Wayfinding and Navigation Processes

3.1.1.1 Familiarization

Virtual exploration consists of using sensory feedback to help travelers familiarize themselves within the context of an environment. With visually impaired travelers, this has been accomplished through spatial audio systems such as the Audio-based Environments Simulator, where objects in the virtual environment correspond with a certain sound as well as spoken words (Sanchez, et al., 2010). Spatial audio systems can be augmented with a force-feedback joystick (vibration-enabled) for a multisensory experience, for which researchers concluded that users were able to develop a better perception of space and location of objects in the environment (Lahav, et al., 2008). If applied to transit systems and stations, virtual exploration devices as such have the potential to help travelers familiarize themselves prior to a trip with the layout of the building or with the layout of the overall transportation network. This type of "scout ahead" capability is already common, to a limited degree, with tools like Google Street View (see [**SOP]**). Audio features would enhance this experience for users who either cannot use tools like Street View or could benefit from redundant audio stimuli.

For people with cognitive disabilities, there is some psychological research of relevance to familiarization for wayfinding and navigation. Such research can have an impact on the design of WaN systems for persons with cognitive disabilities. Mengue-Topio, et al (2011) found that people with cognitive disabilities utilize spatial knowledge differently amongst themselves, which has an impact on the effectiveness of strategies for them to become familiar with a route well enough to learn a short cut. Farran, et al (2012a) examined the use of focal colors, colors that are easy to verbalize, and non-focal colors, colors that are difficult to name or verbalize, as cues for navigating mazes by children with cognitive disabilities and by children without disabilities. Differences between focal versus non-focal colors were seen for memory tests and recall in recounting the cues that a person uses for navigation. Farran, et al. (2012b) investigated whether landmarks were "useful" or "less useful" when familiarizing routes in a virtual environment. In the learning phase, the people with cognitive disabilities took longer to learn than those without disabilities due to errors made at the same choice points in consecutive trials of learning paths through a virtual maze. During the test phase, both groups showed stronger recall of landmarks close to decision points than others. For the group with cognitive disabilities, the ability to recall useful landmarks increased with the individual's nonverbal ability. Therefore, there appears to be merit in the integration of landmarks and route highlighting when presenting navigation information to people with cognitive disabilities.

3.1.1.2 Localization and Orientation

Localization and orientation tools help the visually impaired traveler determine where he or she is at a given moment and provide directions to safely guide the traveler to his or her destination. Example solutions include adding sensors to traditional mobility aids, outdoor smartphone GPS systems, use of landmarks and dead-reckoning on smartphones (Pai, et al., 2012; Pratama, et al., 2012; Tian, et al., 2014), as well as non-smartphone enabled solutions. The former is different than the latter examples since wheeled mobility devices can support larger and more power consuming sensors. Durable frames and large batteries present on wheelchairs, rollator walkers, and scooters allow research teams to install laser scanners, ultrasound, and other sensors for localization (e.g., Simpson, et al 2002).

Simultaneous Localization and Mapping (SLAM) is a technique used in robotics to enable robots to explore an environment, build a map, and localize itself in the map (e.g., Karlsson, et al 2005). This approach builds maps of the world by constantly merging current sensor data with previously collected data. Visual SLAM uses images of the environment with a combination of computer vision and odometry algorithms to map the surrounding space, thus enabling robots to autonomously explore their environment (Karlsson, et al 2005). Presently, although smartphone cameras are becoming increasingly powerful, the phones, themselves, do not have enough cycles and energy to efficiently compute accurate localization, which should be performed onboard or close to the traveler. Some of the technical challenges with SLAM are heights at which obstacles are mapped, the frequency with which the obstacle overlay is updated, and the simultaneous localization of the user within the mapped and updated environment.

Sometimes one method of localization is used to build maps for another. For example, a robot may be used to construct WiFi Received Signal Strength Indication (RSSI) maps based on encoded building plans or a SLAM-generated map. Maps can also be built in parallel if no map is available. This allows a robot to refine position information when one mapping system encounters problems. For example, WiFi RSSI can be used to triangulate position, much like GPS, but it typically cannot achieve the precision of a laser or camera based localization approach. However, lower precision WiFi RSSI is still useful to bootstrap or disambiguate more presice systems.

Camera-based systems (Ravi, et al 2006; Project Tango, 2015) are attractive since they can run on smartphones and wearable camera systems. Typically, these approaches use a database of images of the indoor environment or other visual tracking algorithms to perform localization. While this approach is extremely battery intensive on phones, it could be used periodically to refine position estimates of lower power yet lower precision methods (e.g., WiFi RSSI, etc.).

3.1.1.3 Path Planning, Traversal, and Guidance

Path planning and subsequent monitoring of the path traversal is a rich and continuing research topic within robotics and automated vehicles. Advanced approaches require continuous monitoring of location and orientation, followed by iterative path planning. In other words, planning and traversal are constantly occurring throughout a trip. Sometimes re-planning is paused for computational efficiency until a route deviation occurs or a change in the environment is detected. Since guidance is needed continuously during traversal, planning is also often running in parallel with these processes. Users of Google Maps navigation are likely familiar with this approach since alternate plans can be seen as one moves through the route.

An illustrative example of this type of technology for ATTRI stakeholders is the NavPal system for people who are blind or low vision (TechBridgeWorld, 2015). This system builds WiFi RSSI maps either by sampling autonomously with a mobile robot or by a human carrying a smartphone around the building. Landmarks, door labels, and other features are added either autonomously or by hand. To address dynamic guidance during indoor navigation in more general locations, NavPal integrates indoor localization, sparse map-representation, and an accessible user interface. Specifically, it combines dead reckoning and WiFi signal strength fingerprinting with enhanced route-planning algorithms to account for the constraints of users with visual impairments to efficiently plan routes and communicate the route information with sufficient resolution.

The interface is made accessible via on-screen gestures, voice commands, and audio output. Locations of interest to the user can be stored as phone contacts and effective routes between destinations. While navigating with this tool, the user is given audible navigational instructions at waypoint intervals, e.g., "Head north for 20 meters and then turn left." In addition, the street name and user's direction of travel are announced at intersections. The nearby points of interest are also automatically announced to the user for better localization and orientation. If the user deviates from the desired path at a given setting, e.g., 10 meters, the application informs the user to stop and re-routes a new path to the destination.

A related system that uses camera-based SLAM is being developed and tested under the FHWA Exploratory Advanced Research (EAR) program (Joseph, et al 2013; Xiao, et al 2015). This system goes beyond basic localization to also incorporate features for reading signs and local event discovery. The system includes a variety of sensors and user interfaces, including a body-wornd stereo depth camera and a vibro-tactile belt.

This project is part of a cluster of EAR projects focused on pedestrian mobility by people who are blind or low vision (EAR, 2015). Other projects include new route tracking and following technology for when GPS is unavailable and technology for extending the user's event horizon (i.e., looking further ahead in time and space).

While some products exist on the market for navigation using Bluetooth beacons (see **[INNO]**), continued research in this space has led to more advanced systems. Examples of this include Wayfindr.net (2015) and NavCog (2015; Asakawa, 2015). The HULOP (2015) effort, which is associated with NavCog, also leverages cameras to add vision-based localization, face detection, and activity recognition (e.g., the person in front of you is waving hello). All of these projects are in active development but video demonstrations are available.

Drishti is another tecnological example of an integrated indoor and outdoor infrastructure-reliant navigation tool that does not require a communications infrastructure (Ran, et al 2004). It is a portable computer that uses ultrasonic sensors and a stereo camera to guide a visually impaired user through environments. Though innovative, Drishti requires widespread installation of ultrasound beacons in the built environment. The Wayfinding Electronic Bracelet (Bhatlawande, et al 2013) takes a different approach by relying on a single wrist-mounted ultrasound sensor for basic obstacle detection while deferring all path navigation to the human.

3.1.1.4 Annotation, Update, and Communication

It is also important for travelers to be able to markup maps both for personal use (annotations) and in a public manner (to share information and advocate for changes). Again, NavPal will be used as an illustrative example. The system includes options for users to add routes and audio notes for later use (Min, et al 2015a).

For the annotation component, a user who is blind or low vision can verbally record audio notes and paths travelled for use during future trips. The “breadcrumb” interface allows a user to record messages tied to specific locations on a route which are then automatically played when encounter in the future. Message examples include any potential hazards, a waypoint name, and orientation information for future trips.

Sighted users can also record data on behalf of those with visual disabilities. To reduce the risk of erroneous or malicuios notes, the system allows users to restrict information to trusted sighted users. Examples of trusted individuals could be local transportation providers, property managers (e.g., a building manager), orientation and mobility experts, friends of the traveler, or peers. Trusted users can specify attributes for the data such as (1) characterization of traversability of the waypoint, (2) the proximity of this waypoint to a key landmark, and (3) an estimated lifetime for this data to exist. The users can define a fixed lifetime in hours and minutes or can leave it as an unknown lifetime.

Data from trusted users is stored on a server to support scalable sharing across the community. Users with visual disabilities play an important role in this methodology since the system enables them to share their personal navigational experience with their peers. For example, someone new to an area may want insight on how people with similar disabilities navigate the local transit station or sidewalks.

3.1.1.5 Indoor Maps and Building Knowledge

A major obstacle to ATTRI stakeholders who are attempting to pre-plan trips is the lack of accessible maps for indoor environments and awareness of changes to the environment. Good maps are also needed by many WaN systems that lack SLAM and other mapping functionality. A survey of property managers revealed that the primary reason for this roadblock is the lack of tools to create and maintain accessible maps of the facilities they manage (Dias, 2015). Furthermore, there is no single authority or commercial solution that maps indoor areas like the widely available outdoor map equivalents. Therefore, a solution to accessible indoor maps is likely going to take a different form than its outdoor counterparts.

In general, visitors are expected to be able to navigate buildings by themselves or bring their own guidance assistants with them when they visit most indoor environments. Most building managers and front desk attendants have limited knowledge about the challenges of ATTRI stakeholders and are not always able to assist in useful ways. While tools for automatically generating building maps exist, it is still necessary to document semantic information (e.g., identifying elevators, room numbers, etc.). Technologies for quick and easy development of accessibility maps of indoor environments would be an important step in addressing this gap. Important features in an accessible map creation tool are briefly described below:

- Feature classification: The ability to classify rooms, halls, doors, and types of doors
- Annotation of connectors: The ability to annotate doors, elevators, regular exits, and emergency exits
- Naming areas: The ability to label spaces at different granularities (e.g., office numbers, building names)
- Map updates: The ability to easily update maps when the environment changes or an error is discovered
- Using existing blueprints: The ability to import images/blueprints of floor plans in a variety of file formats and edit them as needed
- Automated information extraction: Automated information extraction from imported blueprints where possible and the ability to easily edit the resulting maps
- Privacy control: The ability to designate areas of maps as private and make other areas of maps publicly accessible or accessible to specific people
- Effective interface: An intuitive interface that is easy to use
- Automated accessibility feature insertion: Automated conversion of resulting maps to information and formats accessible to users

The most relevant advances in this topic are occurring in the building information models (BIM) and computer vision communities (e.g., Xiong, et al 2013).

3.1.2 Transit

3.1.2.1 Wayfinding and Navigation for People who are Blind or Low Vision

Many examples of navigation research technology for people with visual disabilities primarily fulfill the purpose of familiarization (e.g., Geuntert, 2011; Sánchez and Sáenz, 2010). Notable work includes the Train Station Navigation Assistant, a smartphone application designed to provide users with a holistic comprehension of train stations (Sánchez and Sáenz, 2010). In designing the Train Station Navigation Assistant, developers followed best practices for conveying information to users with visual disabilities: “Overview first, details-on-demand.” For example, users are first asked to choose a floor. Upon arriving at the selected floor, users are asked to choose a platform. Upon arriving at the selected platform, users are then asked to choose lines or points of interest (e.g. restroom, elevator, coffee shop, kiosk, etc.). Although this system seems promising, extensive testing has not yet been done. Indeed, a challenge with this system is scalability since a great deal of information must be collected on the station, its structure, and points of interest. Crowdsourcing has been investigated as a way to address the issue of information collection, scalability, and implementation feasibility.

Another familiarization tool for transit stations is the AudioMetro, a software suite for desktop users (Sánchez and Sáenz, 2010). This tool was designed to help simulate and plan trips on the Metro network in Santiago, Chile. The software first utilizes background information on the user to tailor the application experience and interface. Upon inputting the orientation and destination, the user is then able to control a simulation, exploring and making decisions about the route to take in a virtual metro trip prior to actual departure. The software also includes options for guided directions, points of interest and nearby streets, and basic concepts about metros.

Despite the promise demonstrated by many of these systems, there remains a lack of scalable, reliable, and accurate systems for familiarization of transit systems in general for people with visual impairments. No tools exist to integrate familiarization between different types of transit (i.e. transfers involving bus systems and metro). Finally, there is a lack of tools that assist in familiarization with vehicles in transit systems, such as the layout of an airplane or train car.

AudioTransantiago is a mobile phone application for use on a bus that provides the additional benefit of familiarizing the user with the overall layout of the city (Sánchez and de Borba Campos, 2013). The application allows for multiple routes to be planned ahead of time, and the user selects which route is best for a particular situation. The interface for this application includes a high color contrast graphic user interface for low-vision users, and audio text-to-speech with tactile buttons for blind users. During the bus ride, verbal audio output from the user’s smartphone allows the user to anticipate stops and be informed about the streets that are near each stop, allowing for familiarization with the layout of the city while staying oriented throughout the course of the bus ride.

O’Brien, et al. (2014) evaluated an electronic device for use with a long white cane to assist 16 blindfolded users in avoiding above-knee obstacles and obtained inconclusive results. It is questionable whether the use of sighted participants as simulated blind users is applicable. Many research studies in the past have found this does not accurately reflect how people who are blind use technology. We highlight this example here as a cautionary example – ATTRI developers should recruit people with disabilities rather than simulate capabilities in others.

3.1.2.2 Wayfinding and Navigation for Cognitive Disabilities

Livingston-Lee, et al (2014) note how orientation by people with cognitive disabilities is better if navigational instructions refer to terrain features and landmarks as opposed to using cardinal directions (N, S, E, W, etc.) and turns (turn right, turn left). Some additional recommendations from the authors:

- Provide auditory feedback and only give left/right instructions based on which way the navigator is currently facing
- “Prime” individuals concerning upcoming decision points, limit redundant information, and give route instructions from the perspective of the navigator
- Pay special attention to instructions provided at initial orientation, choice points, and destination
- Include the capacity to reassure (to reduce anxiety)
- Adding landmarks for reorientation when lost
- Asking individuals to be stationary (not wandering) while receiving reorientation instructions
- Providing training in both visual and virtual worlds

- Have devices combine GPS with audio and visual cues
- Add personal trackers/locators to provide feedback, location information, to caregivers.

3.1.3 Personal Vehicles

Trip planning and in-vehicle navigation systems generally have limited options for personalized output to individual users. For example, they lack the ability to automatically route around speed bumps, which are dangerous for modified vans. Likewise systems do not learn preferences regarding unprotected left turns, bridges, and other infrastructure elements. Work by Ziebart, et al (2008) illustrated how machine learning systems can build models about these features and provide personalized guidance, which is useful for drivers who find it difficult to drive on certain roads and intersections. Their approach learns both explicit and implicit roadway features so it is not necessary to encode all possible roadway features.

Furthermore, the same underlying algorithms also allow accurate prediction of the driver's destination. This enables a second layer of possible functionality. For example, Davidoff, et al (2011) extended this to predict where parents were driving, thus allowing alerts if planned children pickups or dropoffs were at risk of delay or being missed. Similar capability would be very useful for ATTRI stakeholders with cognitive disabilities.

3.1.4 First / Last Mile and Pedestrian

A good resource for the evaluation of technologies for improving perception of persons with visual disabilities is Bhatlawande, et al. (2014). This article focused on the review of a sonar and visual sensor system to enhance pedestrian navigation in a pedestrian environment (e.g. floor to head-height perceptive range). Evaluated on 15 totally blind persons, the author's system reduced cognitive and perceptual burden on the users compared to when they use only a white cane for navigation. The article mentions other systems and their price entry points: sonic pathfinder, Mowat sensor, Miniguide, LaserCane, and publications that evaluate such navigational technologies. The authors conclude with an assessment of future work: users would like obstacle recognition; distance calibration needs to be tailored to individual user; and users desire increased portability by miniaturizing system components. The authors also recommend that future work should extend to more real-life situations with a larger sample size.

3.2 ITS and Assistive Technologies

As mentioned earlier in this report, there are a variety of ITS technologies that have direct relevance to ATTRI stakeholders. Likewise, the field of assistive technology includes efforts towards better transportation and daily travel. This section summarizes research efforts in these fields and their relationship to the overall ATTRI program goals. A report on a precursor FHWA workshop on this topic is also available (Morton and Yousuf, 2011).

3.2.1 Transit

Research on interior transit vehicle design (D'Souza, 2013) reveals that mid-vehicle bus entry combined with perimeter seating (riders sit with backs to wall, facing each other) is the most preferable and fastest for many ATTRI stakeholders, including people who use walkers or canes. Furthermore, fareboxes with no column underneath allow wheelchair users to swing the front of their wheelchair more effectively between wheel wells when boarding from the front (Steinfeld, et al 2010). The extra space makes it easier to line up a wheelchair on the narrow gap between the wheels. Both of these boarding designs are more feasible when payment is done via smartcards since cash is difficult to collect at a middle door or when there is less space for a cash box. It would be even easier to facilitate rapid boarding if no card swiping was needed. Taking this step would likely require new technologies and research on how they interact with policies. The extreme model is to move to a free fare system, which some municipalities use in certain zones or system-wide. However, such a step is a complicated policy decision and beyond the scope of this effort.

Due to the very long service life of rail vehicles and variations in platform heights at various stations, high performance wheelchair lifts are needed for train car retrofits. The PubTrans4All (2015; Petutschnig, et al 2012) research project developed a “boarding assistance system” lift with a 1.1 meter (3.6 feet) vertical range and the ability to support platform angles of 10 degrees tilt towards or away from the vehicle. This was managed while also maintaining very compact stowed dimensions. This work was led by Palfinger (2015), which continues to advance lift designs for transit vehicles. Newer train models are now able to reach 1.2 meters.

3.2.2 Personal Vehicles

Vehicle modification and custimization for persons with disabilities remains an expensive and time-consuming process. Furthermore, such vehicles often have limited resale value and are hard to arrange as rentals when traveling by other modes. There remains a need for easy modification of vehicles for physical vehicle controls, multi-function dashboard controls, and electronic interfaces. Research on electronic interoperability and dynamically reconfigurable websites in the computer industry suggests it is possible to reach the needed levels of reliability and ease of use. For example, many modern websites that follow accessibility best practices will reconfigure layouts based on screen and font size. This should be feasible for in-car displays for rapid alteration based on user need. Likewise, reconfigurable hardware interfaces for computers are able to reach transmission and reliability speeds well above what is needed for driving. These advances reinforce the potential for similar interfaces in personal vehicles for easy modification (Steinfeld, 2008; Steinfeld 2010). Translating such advances to the automotive industry would allow rapid removal and replacement of vehicle control surfaces using standardized connectors, much like changing a computer keyboard by swapping USB connections.

3.2.3 First / Last Mile

A common barrier in first / last mile travel is unforeseen problems with sidewalks and curbs. Examples include missing curb cuts, sidewalk damage, and in winter when property owners may have failed to clear snow in a timely manner. Ideally many of these barriers would not exist, either due to diligent maintenance or physical improvements to the built environment. Unfortunately, a variety of non-technical factors increase the probability that ATTRI stakeholders will encounter a barrier.

There are a number of research projects underway to improve power wheelchair capability for these kinds of barriers, some of which can manage a tall curb (e.g., Tomokuni and Shino, 2012; Shino, et al 2014; HERL, 2015). Unfortunately, such barriers are still problematic for people who are blind, low vision, or use walking aids or manual wheelchairs.

There are related efforts to develop wheelchairs capable of traversing flights of stairs. A recent example is Scalevo (2015), which drives like a Segway for normal operation and deploys treads when on stairs. The device also has the ability to park in an elevated position, thereby positioning the user's head above typical wheelchair heights.

3.2.4 Pedestrian

There have been attempts to apply robotics perception technology as aids for people with visual disabilities. For example, the MobiFree Cane, Sunglasses, and Echo are a set of wearables and mobility aids that help detect obstacles and notify the user through audio blips or vibrotactile interfaces (Lopes, 2012). Other systems like the SonicGuide uses enhanced sunglasses and ultrasonic waves to convey spatial information to the user (Kay, 2000).

There have also been numerous attempts to replicate dog guides with robots with varying degrees of success (e.g., Kulyukin, et al 2006; Galatas, et al 2011; Hanlong, 2013; Jung, 2014; Woollaston, 2015). These have generally been unable to transition from research to market. One of the traditional challenges in mobile robotics is managing power consumption for all day operation. It is possible this technological barrier will limit such approaches for the near future.

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. This topic includes topics like autonomous vehicles, computer vision, artificial intelligence, and assistive robots to solve a variety of travel related issues important to ATTRI stakeholders.

A technical barrier to entry in use for most robotics systems, whether for military applications, consumer markets or government procurement, is a way of cost-effectively assessing and quantifying an autonomous system's performance, in terms of what the autonomous behaviors do. Key questions include whether the autonomy is making a noticeable improvement in overall performance, adding additional and unwanted risk, and negatively impacting human workload or safety. This is necessary for insurance and regulatory agencies to assess the risk and consequences of an unexpected action, as well as to respond to procurement requirements to assess return on investment. Challenges to behavioral reliability assurance involve developing techniques in which factors that have a significant influence on robotic performance can be identified, measured, and combined so as to achieve model-based prediction of robotic performance. Nascent efforts to asses robot and autonomous vehicle reliability are underway (e.g., Porter, et al 2013; Chaki, et al 2013; Chaki and Giampapa, 2013; Koopman and Wagner, 2016), but are still in the research phase.

3.3.1 Transit

3.3.1.1 Docking

Good docking between transit buses and curbs or platforms leads to tight spacing between the vehicle and the curb or platform, reducing the size of gaps and the need for bridge plates or ramps. Besides aiding accessibility, this also helps reduce dwell time, or the time spent at a stop loading and unloading passengers, thereby improving efficiency and value for all riders. Docking can be even more difficult when driving a 60-foot articulated bus. Tan, et al (2009) explored the use of short-range vehicle automation to support these kinds of docking tasks. As the driver approaches the bus stop the vehicle senses where it is and plans the appropriate motions for precision docking. The driver is alerted to system readiness, relinquishes control, and then supervises the system. Besides improving precision this also frees the driver to allocate more effort towards watching the bus stop and surrounding area for danger. The team deployed this technology in operational field testing in Oregon and California.

3.3.1.2 Personal Transit Vehicles

Several groups have explored mini cars that can be easily stowed for use in car sharing service models. These have promise for people capable of driving at slower speeds and their unusual vehicle designs create opportunities for novel entry/egress. Vehicles with smaller form factors do not occupy as much space in a parking spot or home garage, thus allowing doors to be fully opened for easier entry/egress. Of course, this is moot if the vehicle design requires climbing or contortions to enter. The PMAR Personal Intelligent City Accessible Vehicle (PICAV, 2015) is similar to the Toyota i-Unit concept (2004), but is explicitly designed for car sharing. The PICAV did not appear to reach production, but the CityCar by the MIT Changing Places (2015) team was commercialized by Vitoria-Gasteiz as the Hiriko (Wikipedia, 2015). The passenger cabin of this electric car tilts up for tight parking and rotates down for easier entry and low-profile driving. Like the PICAV, this vehicle is designed for car sharing.

3.3.1.3 Helper Robots

Transit stations and terminals can be complex, confusing places where a wide range of activities and potential obstacles occur getting from one place to another. One idea on how to support independent travel in these locations is to introduce helper robots that live in the facility. Restricting the robot to the building helps in both implementation and use. On the implementation side, this allows the robot to have a complete map of the building, reliable internet connectivity, easy access to power and charging stations, and a constrained information database and vocabulary. Bounding the scope of the robot’s world and knowledge dramatically reduces challenges associated with localization, navigation, artificial intelligence, learning, and natural language.

Robot assistance can range from completely manual control by humans all the way to fully autonomous behaviors. The former is quite useful for basic tasks, like helping with physical transfers between wheelchairs and seats (e.g., Wang, et al 2014) or teleoperated assistance (e.g., Cooper, et al 2012). The latter may be very helpful in tight quarters where a transfer is needed but the mechanical assistance needs to be moved due to weight or other logistical issues. For example, the Strong Arm (Wang, et al 2014) could be mounted on a base and moved from the terminal and down a parked airplane aisle. Teleoperated assistance is when a remote person helps control devices like wheelchair mounted robot arms. This can improve task performance and experience, especially when the user has very limited manipulation ability.

At the next level are robots that follow users and carry heavy items, sometimes called "mules" in defense contexts, which could be useful when travelers have luggage in tow. These robots typically track the user and mimic their route (e.g., Aalto University, 2015; Boston Dynamics, 2015). Automated delivery of objects is also possible and has been deployed in hospitals for some time (e.g., Aethon, 2015). It is possible such robots could be tasked to take luggage or groceries at the entrance and meet the user at a platform. Research teams are now exploring how autonomous robots can provide assistance in close proximity to their users (e.g., Personal Robotics Lab, 2015; Toyota, 2015).

Most assistance robots are wheeled for power efficiency and speed, but legged robots are an option. Wheeled robots are similar to wheelchairs in terms of access, so legged robots may be necessary for inaccessible stations which will not be updated for cost or other reasons. Legged robots that can transport a wheelchair user up stairs are probably not an efficient mechanism due to the required power and risk of being stuck during failure. Due to the nature of the task, it is probably safer and cheaper to use a portable stair lift (e.g., Alber, 2015; Garaventa, 2015) or develop a similar single-purpose solution.

Researchers are also currently working on helper robots to assist as guide robots, information providers, and object manipulators. In the area of guidance, several efforts to date have focused on smart canes (e.g., Ulrich & Borenstein, 2001), dog guide style robots (e.g., Galatas, et al 2011), and robotic shopping carts (e.g., Kulyukin, et al 2006).

Robots serving as receptionists at information kiosks or as mobile information resources (e.g., Toyota, 2015; Honda, 2015; ATR, 2015) have been tested in variety of locations. These are interesting and often entertaining for visitors but are typically of limited functional value. However, when combined with manipulation capability there are some interesting use cases for environments where it would be not cost effective to station an employee 24 hours a day. Assistive robots must be able to effectively interact with persons with disabilities, including travelers who have difficulty seeing the robot. User expectations and cognitive models of robots that will physically interact with them are heavily influenced by the visual appearance of the robot and what actions are witnessed prior to interaction. Min, et al (2015b) addressed this challenge by exploring meaningful ways for robot assistance by gathering data from sighted experts (e.g., orientation and mobility specialists) and people who are blind or low vision during in-person robot experiences. They also surveyed robotics experts and members of the general public to learn how they might describe the robot (a Rethink Robotics Baxter) to someone who asks for a description. Findings revealed significant diversity in how to describe the robot, which suggests tailored or sequential branching self-introductions by robots may be necessary.

3.3.2 Personal Vehicles

3.3.2.1 Alternative Driver Vehicle Interfaces

Shortly after the DARPA Grand Challenge, the National Federation of the Blind (NFB) reached out to competition participants with an interesting question. They wanted to know if the technologies used for autonomous driving could be adapted to translate sensor data into usable information for blind drivers. The idea behind this approach was to leave the cognitive parts of driving in the hands of a human, thus bypassing some of the more difficult aspects of autonomous driving (e.g., deciding what to do when other cars are not following the rules of the road, etc.). The concept was named the Blind Driver Challenge (2015).

NFB proceeded to partner with the Robotics & Mechanisms Laboratory (2015) from Virginia Tech University and demonstrate a prototype system on the Daytona International Speedway (Barry, 2011). This was accomplished through several novel driver interfaces that used vibrations. The team also explored arrays of miniature air jets. NFB has since collaborated on other concepts, like a three wheeled motorcycle test over 55 mph on the Bonneville Salt Flats. These were interesting demonstrations and it is possible there is broader merit in this general technology approach. Given the visual complexity of driving in suburban and urban locales, this may be worth revisiting when vehicle autonomy is good enough to assist through semi-autonomous methods.

As noted in Morton & Yousuf (2011, p.16) an important concern is the “event horizon” - i.e., the perceptual distance needed to become aware of an obstacle. For white cane users, this is usually the length of their cane. If jogging with a perception assist system, it would be some distance down the sidewalk. While driving, the distance can grow dramatically and a safe range could reach beyond sensor distances at highway speeds. Managing the event horizon will likely be the next big challenge for research on topics similar to the Blind Driver Challenge.

3.3.2.2 Parking

In between today’s semi-autonomous parking assistance systems and autonomous parking garages are systems that allow cars to autonomously park themselves in lots and garages. Allowing the driver to exit at the curb means the vehicle can park anywhere, even in regular parking spots that would normally be too tight for the driver. This also allows caregivers to exit at the curb too. Since this mimics regular valet service, this concept is sometimes called a virtual valet (Suppé, et al 2010).

Parking in lots has been demonstrated many times and is easier due to the unobstructed views of the sky, thereby allowing use of high precision GPS. Parking with only map knowledge of a garage is harder, but possible with laser scanners and similar sensors. Suppé, et al (2010) demonstrated a virtual valet in this manner. Driver management of the vehicle occurred through state-level control (e.g., go, stop, pause, etc.) rather than direct teleoperation of steering wheel and pedals. A state-level approach with autonomous driving eliminates many of the well-known human factors problems present when teleoperating remote vehicles. The user could exit the car at a curb, command the vehicle to autonomously park from their phone, monitor live video feeds from the forward and back cameras, and pause the vehicle if needed. When ready, the user could issue a retrieval request for the car to return. The system also utilized a safety layer to pause when an obstacle encroached into the car's planned route. The team subsequently transitioned from laser scanners to a single camera for localization and positioning.

Since this research effort, various companies have demonstrated similar concept systems. These use a variety of sensor techniques, sometimes involving infrastructure-based sensors or assistance. In 2013, demonstrations were shown by Audi (Stoklosa, 2013), Valeo (2015), and Ford (Ross, 2013). Tesla released a simpler version of this called Summon in early 2016 that can manage straight paths in and out of a parking spot (Tesla, 2016). As with Suppé, et al (2010), these were all state-level control approaches. The likely issues for commercial release are liability and safety. It may be possible to alleviate these by only allowing use in controlled environments, like protected portions of garages or with sensors designed to detect pedestrians to protect both users and bystanders.

3.3.2.3 Emergency Parking

Another form of autonomous parking is autonomously pulling over to the curb when the driver is incapacitated. There have been research efforts designed around detecting heart attacks and similar acute events that could lead to crashes. Strokes and heart attacks are a key concern for senior drivers with certain health conditions. The core concept is for the car to assume control just long enough to pull change lanes and come to a stop. The short-term nature of this autonomy dramatically simplifies the level of difficulty. The core technology is comparable to adaptive cruise control with a constantly lowering speed setting combined with optical tracking of the curb and safe lane changing. Since this would be an emergency event, it would also be reasonable to start honking and flashing lights to alert neighboring drivers so they can provide space for the lane change, if needed.

3.3.2.4 Platooning

Platooning is when vehicles use a virtual towbar to link up and follow a leading vehicle. This is an extension of adaptive cruise control where communication between vehicles is important and lane keeping is introduced. Some of the early efforts to explore this concept in depth were the CHAUFFEUR I and II projects (TRIP, 2015). These focused heavily on commercial vehicle operations as driver relief can have a big impact on safety and efficiency. Also, the added cost of the systems is more reasonable when examining the base cost of a commercial vehicle. The subsequent SARTRE (2015) project explored personal vehicles platooning behind a professional, commercial truck driver. The next step, where all vehicles in a platoon are autonomous, was a central element of the National Automated Highway System Consortium (NAHSC) demo in 1997 (e.g., Ferlis, 2007). Similar concepts continue to be explored by various research teams.

While the mass-market deployment is still unclear, coordinated platooning where the driver can relinquish control has direct value to ATTRI stakeholders. For example, it can provide relief to drivers who are easily fatigued or become bored on long drives. Boredom is a real issue for people who cannot use audio entertainment. Likewise, platooning provides a mechanism for those who are uncomfortable driving at highway speeds for more than a short distance.

3.3.2.5 Full Autonomy

Following the NAHSC, numerous teams explored methods for vehicle autonomy, especially in urban areas. These are far more complex and unpredictable than highway driving and DARPA wanted to see faster progress. The Urban Grand Challenge was initiated to spur more rapid advancement in the state of the art. By all accounts, this was effective. Numerous teams demonstrated the ability to complete the course and advances in technology occurred (e.g., Darms, et al 2009; Urmson, et al, 2009). Multiple industry-sponsored and led teams spun out of this competition.

The Google Car team (2015) is attracting most of the current attention due the high mileage attained and their significant technical accomplishments. From an ATTRI perspective, the team has illustrated the potential power of autonomous vehicles with the help of Steve Mahan, who is blind and was shown "driving" to a nearby restaurant for drive-through tacos and a trip to the dry cleaner (Google, 2012). In this clip Mahan remarks that having a self-driving car can give him the autonomy of doing things for himself on his schedule. Subsequent demonstrations show other ATTRI stakeholders experiencing rides in Google's custom built autonomous vehicles (Google, 2014; Lijas, 2014). These new vehicles lack driver controls, so manual operation is not feasible and there is no steering wheel restricting vehicle entry. This should lead to more accessible vehicle designs.

At the time of Mahan's drive the legality of the trip required negotiation between Google and the local police force (Hackman, 2012). There are now laws in California and several other states which create procedures for formalized, legal autonomous driving.

A recent autonomous vehicle competition in Korea (Ackerman, 2014) revealed how inclement weather and unusual roadway conditions can be problematic. On the second day of competition it rained on the course, so the reflectivity of the paving surface changed quickly and varied widely throughout the course, making it difficult to adjust vision sensors for recognizing objects. Street signs could be detected against the gray background of cloud cover, but if there was a brief break in the clouds, the background illumination would cause street signs to be completely missed. Reflections from the wet surface of fast-draining pavement made it difficult for one vehicle to track lane markers and paint and detect a cement curb. Interestingly, these problems are similar to those experienced by some ATTRI stakeholders when driving in inclement weather. Solutions for autonomous vehicles are also likely to be useful for driver assistance and monitoring systems.

Uber has also recently attracted attention for a new focus on autonomous vehicles (Newman, 2015). The stated focus is to advance the possibility of autonomous taxi service models. The implications of this are discussed later in the document.

3.3.3 First / Last Mile

As seen in the NAHSC and in automated factory materials handling robots, trips along prescribed routes are much easier than regular driving. Several groups are using this fact to deploy neighborhood autonomy using small shuttles. In Europe this is occurring through the CityMobil2 project (2015) and associated partners (e.g., BestMile, 2016). Multiple sites are exploring the application of various vehicle types in public service. What sets this effort apart from existing unmanned people mover approaches is operation in mixed traffic and an attempt to move from a simple linear path to point-to-point service within a street network. There is already anecdotal evidence that ATTRI stakeholders are utilizing CityMobil2 demonstrations for improved quality of life. Aside from technical challenges and finding ways to preserve safety, a key issue appears to be legal codes. This is similar to issues experienced by Google.

Many of the legal concerns are reduced when autonomy occurs within “less” public areas or constrained environments. The TARDEC ARIBO program is taking advantage of this and exploring neighborhood autonomy within United States military bases and other private campuses (Brooks, 2015; O’Connor, 2015). The Ft. Bragg deployment is especially interesting as the system will traverse routes valuable to a wide range of users, thereby permitting a better understanding of how to socialize autonomous vehicles and novel service models with the general public. Furthermore, the route will include a connection to external transit service for multimodal trips. Aside from technical and user issues, this research project will also include performance and cost evaluation. This should help when estimating impact for similar systems funded through non-military sources. Other vehicle autonomy test sites are now open or planned in various other parts of the country (e.g., Mcity, 2016; GoMentum Station, 2016; Babcock Ranch, 2015).

Another possible robotics application within the first / last mile are snow removal robots along sidewalk routes. This is probably too big of a challenge within the immediate future due to the safety implications, but current research on excavator robots for the moon and Mars may be applicable for such applications. However, the significant forces needed to clear heavy snow or ice would likely require a rotary snow blower mechanism, which is unlikely to be tolerated for autonomous operation due to safety issues.

Wallich (2012) humorously explored the desire of parents to know their child safely reached a destination through the use of a modified consumer drone. The drone was designed to follow the author’s child from home to the nearby bus stop, which seems silly for most parents but is an interesting concept for some caregivers of ATTRI stakeholders. In reality, similar capability is probably feasible with just a smartphone app.

3.3.4 Pedestrian

3.3.4.1 Path Planning and Routing

It is easy to tell a robot to go from one waypoint to another, but dynamic events along the route can lead to variations in travel. For example, a guide robot may need to dodge pedestrians, weave around a pile of leaves, etc. These subtle details fall within the robotics area of path planning. Unlike traditional wayfinding and navigation, this task requires planning under uncertainty, typically through the use of soft constraints and dynamic replanning to account for changes in the scenario. An example for the former is a robot electing to drive through leaves if avoiding them is too difficult. Another aspect of path planning for robotics is the incorporation of robot capabilities and features. Accounting for capabilities, using soft constraints, and continuous replanning are similar requirements for people with disabilities. Therefore, any robots used for pedestrian guidance or safeguarding will need to utilize these strategies.

3.3.4.2 Perception and Prediction

As mentioned in the corresponding section of **[INNO]**, there are a number of sidewalk assessment tools in use today that are either pushed or driven by human operators to collect georeferenced information about sidewalk quality. There are two robotics advances on the horizon. First, there is research underway to apply camera based road surface assessment to sidewalks (Mertz, et al 2014). This would dramatically lower the cost of this approach and allow maintenance crews to better manage deployment of the more costly sensor systems. Second, it is reasonable to assume sidewalk assessment robots could drive around neighborhoods autonomously after a few years of development. It is straightforward to use cameras for tracking the sidewalk but methods for managing driveways and intersections would be needed. Techniques for perceiving and understanding road signs and traffic signals are likely to be important (e.g., Gu, et al 2010; Parada-Loira and Alba-Castro, 2010).

These methods are good for understanding the sidewalks, but not for understanding how people use the sidewalks or where they are going. If robots are going to mix with people it is critical that they understand where people are and generate estimates about where they are heading. This challenge is also important in surveillance applications. Therefore, there are numerous projects on detecting, tracking, and predicting where pedestrians are heading.

Discerning some pedestrians from other vehicle classes can be challenging for computers. While not directly addressing ATTRI users, an extension to the class of vulnerable road users (VRUs) can be imagined. For example, detecting a bicyclist is very challenging since they change shape (moving legs) and their speeds are often very different from nearby vehicular traffic. In some respects they have characteristics of a pedestrian, in others, those of a vehicle. A manual wheelchair user might be classified within the same spectrum. The human occupant also changes shape (moving arms) and their speed is akin to that of a bicycle, especially for racing wheelchairs. The easiest way for a computer to classify bicycles and wheelchairs is via images. Therefore, it will be important to use vision-based systems (e.g., Cho, et al 2010;

Jungling and Arens, 2010; Nakatsubo and Yamada, 2010) to explore how mainstream pedestrian detection and tracking techniques perform with ATTRI stakeholders.

Predicting where pedestrians will travel (e.g., Kitani, et al 2012) can be a very powerful tool for ATTRI applications. Aside from just trying to better route pedestrians in less structured areas (e.g., plazas), this can also be used to infer the speed of a pedestrian and whether they are likely to enter a dangerous area. For example, this could be very useful when deciding if a pedestrian is likely to cross a street within an allotted time or to infer if they are heading to the correct train platform.

3.4 Data Integration

This technology area includes solutions that enable the integration of data and information systems to create and expand accessible transportation applications. There are 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. For example, developers may opt to add details about vehicle fullness to an existing transit data specification. 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.

As noted in Morton and Yousuf (2011), data sources are likely to be integrated across multiple systems rather than a single integrated framework. In fact, some of these data sources will not be transportation related, but may be generated by transportation users or other sources. Mainstream computing trends, like crowdsourcing, open data, data mining, data aggregation, etc are all important elements in new intelligent transportation systems.

3.4.1 Cross-Cutting

3.4.1.1 Open Information

As mentioned in the **[SOP]** document, General Transit Feed Specification (GTFS) and GTFS-Realtime are the de facto standards for data interchange of relevance to public transit. This data interchange structure captures information of relevance to most fixed-route transit users: commuters and the people who serve them. An effort has been proposed by a consortium whose members include: RideScout (now Moovel Transit), TriMet, CUTR, Trillium Transit, IBI, and the Technology Association of Oregon, to extend the GTFS specification to include additional annotations of relevance to shared-use mobility, hence GTFS-SUM (Shared-Use Mobility). The vision of this effort is to, "Support the next generation of shared use mobility software, facilitating awareness of and access to carshare, bikeshare, rideshare/carpool, ridesourcing, shuttle and mass transit options" (GTFS-SUM, 2015a). An SDK to support application development for GTFS-SUM (2015b) has been released.

The initiative is envisioned to support five information needs (GTFS-SUM, 2015a):

- Locations, real-time (current) and future (probabilistic) availability and pricing for non-mass transit, station-based services and vehicles.
- Locations, real-time (current) and future (probabilistic) availability and pricing for non-mass transit, zone-based services and vehicles.
- Locations, real-time (current) and future (probabilistic) availability and pricing for zone-based dynamic mass transit services and vehicles.
- Price/fare integration between the above and traditional mass transit modes.
- Connection protection: likelihood of making a particular mass transit connection.

3.4.1.2 Ad hoc Semantic Interoperability of Information

Designing future intelligent transportation systems as an integrated and composable information system architecture holds promise as a way of addressing the varied and individual needs of the target users of this report. Real-time information from multiple, dynamic, and disparate sources is key to situation awareness and mobility within geographically and technologically distributed systems or environments of varied scales. Data can derive from multiple, unexpected sources, so there is the need to discover it, which is still a difficult challenge given: network topologies, data pacing, and routing policies (e.g., Sycara, et al. 2003).

The ability to apply data in the context of the user's goals is a data interpretation problem that requires goal and context. This is similar to research in other domains and stakeholders (e.g., Sycara, et al 2009; Giampapa, et al 2001). While simple rule-based approaches are feasible, an important challenge is to enable robust understanding of human intention in context. Likewise, simple approaches do not support on-the-fly incorporation of new information services. In an ideal world, systems will adapt without human programming when a new service is offered. For example, a WaN app could detect that a new real-time arrival information source has been deployed and switch to it from a static schedule information service.

In service oriented architecture (SOA) applications, it is also common to encounter the description of a service in terms of a data description that is different from intended. For example, there are multiple online weather services for cities. Yet, some service providers will define a city as the geopolitical entity that is served by a major international airport, by government census data, or by postal Zip codes. What constitutes useful weather information is also subject to interpretation and conversion: there are reporting intervals for history, updates and forecasts; there is the issue of what is reported: temperature, precipitation, wind, net effect on a person outside, etc.; and differences of units of measure. These heterogeneities of data and data types are easy for humans to resolve, but very difficult for information technology to resolve autonomously without appropriate interchange markup and some human intervention.

This problem is called the *semantic interoperability problem* by the autonomous systems community. The ad hoc leveraging of a service – extracting what is necessary, combining and translating data with other ad hoc services – when studied as its own, not completely solved problem, is referred to as *dynamic service composition*. Decades ago, these two problems were recognized as a database schema interoperability problem by the database community. Unfortunately, demands for integration of databases required processes performed by humans that could last days to weeks, not seconds or fractions thereof. This motivated development of new approaches. Algorithms for solving semantic interoperability problems are called *matchmaking* algorithms, and vary widely in sophistication.

Other issues involved in the autonomous and ad hoc integration of data include machine readable and enforceable policies. An example of a policy is the “Do Not Track” policy that is built into web browsers that allows a human browser user to request that their online activities not be tracked by web sites. It was based on a similar W3C (World Wide Web Consortium) policy that a website can request that it not be indexed automatically by search engines or used by automated services, by posting a “No Bots” policy. At issue is the dynamic tension between creators of content wanting to maintain control over it, and its potential to value added resellers. The internet requires both types of participants, and both participants need each other to a certain degree. Regulation by clearly articulated policies keeps both sides interested in participating.

Similar issues exist for government agencies. In the U.S., federal agencies are restricted in what data they can collect on U.S. citizens. Such data must be only pertinent to an agency’s function. Federal agencies cannot share that information with other government agencies. Dilemmas occur when federal agencies purchase private sector services that aggregate data from multiple sources, including other federal agencies. If this is to be done electronically by autonomous systems, machine-readable policies and markup need to be designed into such integrated data systems.

Technological solutions to such problems exist. The autonomous agent community, with the support of DARPA, started the DAML (DARPA Agent Markup Language) program in the early 2000s, which transitioned to international adoption as the W3C OWL (Web Ontology Language; W3C, 2001) standard. The adoption by the web services community is often referred to as the *Semantic Web*, and sometimes as *Internet 2.0*.

Autonomous systems and personal devices, while potential utilizers of Semantic Web technologies, have very different needs; mainly, their computational machinery must be very lightweight, low power, and fast. Architectural ways of addressing this are to offload the burden of computation to a remote server as much as possible. A research challenge is finding ways to manage this balance without sacrificing user interaction and overall performance.

3.4.1.3 Wireless Communication Technologies

Due to the mix of both regulatory uncertainty around DSRC and the possibly uneven market penetration, it is important to consider a wide range of wireless technologies for communication with users. Examples of likely tools include DSRC, 3G, 4G, Wi-Fi, and Bluetooth (Morton and Yousuf, 2011, p. 9). These have various degrees of real-time performance, bandwidth, and range but all benefit from the ability to operate in non-line of sight conditions. This is important when dealing with crowded environments and inclement weather.

In cases where line of sight operation is feasible, it is also possible to utilize optical techniques like QR codes (printed or on screen), image watermarking (e.g., Ishizuka, 2014), and optical character recognition (e.g., Coughlan and Shen, 2012; Gonzalez, et al 2012). The latter, which involves recognizing letters in images and converting them into text, may not seem like “wireless” communication, but it is still a form of information transmission.

There are many privacy concerns specific to ATTRI technologies (Baker, et al 2017). One concern, and a focus within the U.S. DOT and many research teams, is communication security to avoid fake data, dangerous intrusions, or loss of privacy (e.g., Liao, et al 2013). This is also an issue for ATTRI stakeholders since people with disabilities are at higher risk of street crime. There is anecdotal evidence that some users do not want systems that reveal their disability to criminals. Fake systems are also a concern, like stickers with malicious QR codes. Some ATTRI stakeholders lack the ability to detect evidence of this kind of attack.

3.4.1.4 Data Integration and Machine Learning

One of the big challenges for travelers who have visual disabilities or difficulty navigating complex tables is reading schedule grids on websites. This can be compounded by accessibility barriers within the website code, thus blocking use through screen readers. One research project is exploring how to mix machine learning with crowdsourced system training to create re-usable scripts for data integration and table summarization (Gardiner, et al 2011; Gardiner, et al 2015). Current results are promising and suggest this is feasible for a large number of websites, which should allow people who have trouble with complex websites to use data retrieval and integration scripts constructed by caregivers and travel trainers.

On the service provider side, there are many opportunities to mix system dashboard interfaces (e.g., Barabino, et al 2014) and machine learning. This is already being used by some regions to predict traffic congestion up to one hour in advance (IBM, 2015) and pre-position crews for more rapid response to large-scale emergency events (Lo, 2013). On the research front, the Center for Advanced Transportation Technology (CATT) Lab (2015) at the University of Maryland has developed a number of transportation data visualization tools, some of which use real-time data. Some of the same prediction and user interaction techniques for these kinds of systems are likely to be useful to service providers for visualizing, detecting, and predicting transportation issues associated with ATTRI populations.

3.4.1.5 Crowdsourcing and Participatory Sensing

Within the research community, different terms are used for *social computing*, which are computational techniques that gather data from end users:

- **“Crowdsourcing**: Combines the concept of ‘outsourcing’ with the concept ‘wisdom of crowds,’ the idea that many people working together are smarter than a few people working in isolation... Examples include the content recommenders found at Amazon and Netflix; Wikipedia, a community-constructed encyclopedia; Twitter, where the comments of users reveal unfolding trends; and Mechanical Turk, which makes thousands of workers around the world available to perform small tasks.”
- **“Participatory Sensing**: Views the ever-increasing number of mobile phones in the world as a new type of instrumentation and a new source of sensor information... Modern smartphones can sense their location, movement, noise and light levels. In addition, people with smartphones can easily share their observations of unfolding situations from civil unrest to blizzards.” (Steinfeld, et al 2014, p. 165)

The RERC on Accessible Public Transportation developed a transit rider information system, called Tiramisu, to act as a testbed for research to explore how to use universal design, social computing, and service design to provide value for all transit riders (Zimmerman, et al 2011). When initially released in Pittsburgh, the local agency did not have automatic vehicle location (AVL) installed. Tiramisu allows riders to trace and spot buses, document vehicle fullness, and submit notes about their experiences. Research on system performance showed good coverage and low error rates (Tomasic, et al 2015), high user satisfaction (Zimmerman, et al 2011), and a willingness by riders to contribute data to the community (Tomasic, et al 2014). There was also evidence that riders without disabilities would document evidence of service breakdowns that led to accessibility barriers (Steinfeld, et al 2012).

The team’s current active research is exploring how simpler forms of data contribution influence behavior, the impact of merging the newly introduced AVL with crowdsourced data, how real-time information impacts riders with disabilities, whether such data can be used to reduce user interaction effort, and whether this kind of social computing system impacts social inclusion.

Other examples of crowdsourcing include contributions by knowledgeable parties for better travel experiences. Currently, the best way to gather data about good strategies or current information about a transit station is to ask friends, family, and co-workers for their advice and knowledge. In unfamiliar locations, like a strange airport, it is possible to ask fellow travellers on message boards and community sites (e.g., TripAdvisor, Flyertalk, etc). Research teams are also starting to explore how time and location sensitive crowdsourcing can support these information needs. For example, users of VizWiz (2015) can take a picture, add a question, and get timely responses back from crowdsourced help. This idea has been successfully extended to video where a group of people help describe video clips (Lasecki, et al 2013). Another example is the concept of having trusted sources document routes and georeferenced voice notes for navigation assistance by people with disabilities (e.g., Min, et al 2015a).

Bus Stop CSI (Hara, et al 2015) takes a narrower focus and attempts to gather and maintain updated, detailed information on bus stops for riders with visual impairments. Further improvements in this space could include verification of a bus stop through another street view provider and expanded list of important landmarks to be noted.

3.4.1.6 Systems Engineering Challenges

A variety of systems engineering terms and vocabulary have been introduced in the **[INNO]** and this document. This section is intended to provide an overview of those terms, and introduce others that are related to them.

Intelligent transportation systems (ITS) have characteristics of systems engineering disciplines that are still being studied and developed in significant ways:

- system-of-systems engineering (SoSE) (Maier, 1999; Luzeaux, et al., 2013; Jamshidi, 2008),
- ultra-large-scale (ULS) systems engineering (Northrop, et al., 2006),
- edge-enabled systems engineering (Sullivan, 2007; Hall, et al., 2010),
- cyber-physical systems (CPS) engineering,
- socio-technical [eco-]systems engineering,
- autonomous systems engineering, and
- collaborative systems engineering.

As mentioned in the **[INNO]** document, some ITS system-of-systems (SoS) characteristics are: operational and managerial independence of its elements, evolutionary development, emergent behavior, and geographic distribution. These characteristics create novel challenges to the institutions and multiple levels of government that must cooperate in the specification of policy, design, acquisitions and evaluation of ITS.

A ULS system has all of the characteristics of a SoS, but at a much greater scale. The implications of scale have an impact on the traceability of stakeholder business needs to identified quality attributes to overall system architecture, to the assessment of the overall system performance. The autonomous and socio-technical aspects of ITS remind us that individual elements will likely depart from their prescribed behaviors, or at least be subject to multiple behavioral norms that can render the estimation of their compliance and overall system-level performance difficult. Since we are concerned with the elements not as individuals as much as communicating, socio-technical entities, the CPS engineering aspects are considered to the extent that they provide an avenue by which security from malicious manipulations can be enhanced. The best counter-measures to the malicious manipulation of CPS entities via their cyber-only interfaces is to not effect an action unless the physical state can be verified by multiple sources.

Technologies of multiple maturity levels exist that can accommodate and reduce the complexities and engineering challenges of ITS. Some of the most comprehensive scientific research and development for this have been in a field that is now identified as *autonomous agents and multi-agent systems (AAMAS)*. Initially proposed as the study of distributed artificial intelligence (DAI), AAMAS studies and engineers ad hoc semantic interoperability of autonomous and user-proxy services as a socio-technical discipline that encompasses such ITS-relevant areas as: computational mechanism design, game theory, negotiation theory, computational theories of cooperation, collaboration and teamwork, semantics, systems design and engineering.

3.4.2 Transit

3.4.2.1 Data mining

One of the big questions in public transit is whether real-time arrival information has an impact on transit riders. Real-time arrival information has already been shown to improve rider perceptions of security (Ferris, et al 2010), which is important for many ATTRI stakeholders. Recent research by Breakwood, et al (2014) on the general population shows that it can also impact many other factors important to ATTRI stakeholders. Riders experienced a large drop in "usual" wait times, less anxiety and frustration, and higher levels of satisfaction.

The daily use of transit by large numbers of people also allows for interesting data mining functionality. As a simple example, the Tiramisu system surfaces a historical estimate for riders when no user is currently sharing data about a vehicle but enough historical data for the specific bus trip has been collected on prior days (Zimmerman, et al 2011; Tomasic, et al 2015). Similar ideas explore the concept of creating dynamic stops and routes based on end user demand and location. For example, Mishra and Lopez-Bernal (2014) describe a complex process for mining user trip requests to schedule dynamic routes and stops. Bridj (2015) uses methods like this in a narrower form. It is also possible to mine data for insights on how to adapt existing service. For example, many teams have also looked at smartcard fare data for origin-destination research (e.g., Nassir, et al 2015).

Data mining, both at these small and large scales, provides interesting opportunities to identify how ATTRI stakeholders are using transportation networks and how to automatically detect when help is needed, what services are not serving their needs, and where inefficiencies are present in the system.

3.4.2.2 Integrated Service

The current Integrated Dynamic Transit Operations (IDTO, 2015) field test is a good example of how various transit services can be integrated into a single user experience. This level of integration is very helpful for ATTRI stakeholders who have difficulty managing and planning across multiple service modes. Furthermore, the centralized smartphone application provides opportunities for user-responsive services beyond traditional apps.

As a summary for readers unfamiliar with the IDTO field test, some highlights are listed here. U.S. DOT defines the IDTO bundle as the following three applications:

- **"T-DISP**: T-DISP seeks to expand transportation options by leveraging available services from multiple modes of transportation. Travelers would be able to request a trip via a handheld mobile device (or phone or personal computer) and have itineraries containing multiple transportation services (public transportation modes, private transportation services, shared-ride, walking and biking) sent to them via the same hand-held device. T-DISP builds on existing technology systems such as computer-aided dispatch/automatic vehicle location (CAD/AVL) systems and automated scheduling software. These systems will have to be expanded to incorporate business and organizational structures that aim to better coordinate transportation services in a region. A physical or virtual central system, such as a travel management coordination center (TMCC) would dynamically schedule and dispatch trips. T-DISP enhances communications with travelers and presents them with the broadest range of travel options when making a trip.
- **T-CONNECT**: The goal of T-CONNECT is to improve rider satisfaction and reduce expected trip time for multimodal travelers by increasing the probability of intermodal or intra-modal connections. T-CONNECT will seek to protect transfers between both transit (e.g., bus, subway, and commuter rail) and non-transit (e.g., shared ride) modes, and will facilitate coordination between multiple agencies to accomplish the tasks. In certain situations, integration with other IDTO bundle applications (T-DISP and D-RIDE) may be required to coordinate connections between transit and non-transit modes, and between public and private transportation providers.
- **D-RIDE**: The Dynamic Ridesharing (D-RIDE) application is an approach to carpooling in which drivers and riders arrange trips within a relatively short time in advance of departure. Through D-RIDE, a person could arrange daily transportation to reach a variety of destinations, including those that are not serviced by transit. D-RIDE serves as a complement subsystem within the IDTO bundle by providing an alternative to transit when it is not a feasible mode of transport or is unavailable within a certain geographic area. The D-RIDE system would usually be used on a one-time, trip-by-trip basis, and would provide drivers and riders with the flexibility of making real-time transportation decisions. The two main goals of the D-RIDE application are to increase the use of non-transit ride-sharing options including carpooling and vanpooling, and to improve the accuracy of vehicle capacity detection for occupancy enforcement and revenue collection on managed lanes. As a result of accomplishing these two goals, a myriad of other benefits could exist that benefit transit systems, including that D-RIDE could help reduce peak demand for public transit so the public transit system can be designed more affordably and can have greater customer satisfaction during spikes in ridership." (IDTO, 2015)

T-DISP has similarities to flex routing and information aggregation apps like RideScout. D-RIDE is analogous to ride sharing systems like Carma and Commuter Connections. These three systems are described in the **[INNO]** document.

The pilot deployment for this project is occurred in the Columbus, Ohio region under the public name C-Ride (2015). Timcho (2015) provides additional detail on plans and user interfaces. Of the planned functionality, the T-DISP and T-CONNECT are most interesting for the ATTRI community. T-DISP has the potential to modernize flex routing in ways that make it responsive for spontaneous travel, thus enabling trips that previously would need to be planned a day or more in advance. This supports unforeseen employment related, health, and social trips. T-CONNECT is very useful for people who move a bit slower between connections or need more time to board or egress vehicles. These have implications for transit agency costs too, as it may lower dependency on paratransit services.

3.4.3 Personal Vehicles

While DSRC is the expected mode of communication for many of the functionalities discussed below, there are alternative options. In fact, many research teams do not have access to DSRC so they use WiFi, cellular, and other technologies to explore system designs and performance.

There are numerous research teams and projects exploring effective communication and the data-oriented systems described below. In the interest of brevity, the focus below will be on the implications for ATTRI stakeholders, rather than a dense summary of individual research projects.

3.4.3.1 Vehicle to Vehicle

As mentioned above, automated platooning is most effective when vehicles in the chain are sharing real-time information. This helps eliminate latencies in perceiving a change in speed for the lead vehicle. Typical congestion shockwaves are a symptom of compounded latencies since increased brake pressure is needed to preserve safe distances. Cooperative cruise control is a form of adaptive cruise control where cars in a chain share speed and accelleration information to mitigate the need for severe braking. Likewise fully autonomous vehicles and collision avoidance systems also benefit from more timely information about lead vehicle speed and deceleration rates. All of these help ATTRI stakeholders who normally would have difficulty braking quickly and safely during a congestion shockwave.

3.4.3.2 Vehicle to Infrastructure

Many ATTRI stakeholders avoid unguarded left hand turns since they have trouble perceiving safe gaps between vehicles or reacting in time to initiate turns when gaps appear. The Cooperative Intersection Collision Avoidance System (CICAS) project (Misener, et al 2010) explored how vehicles and intersections could communicate with each other to provide safer vehicle crossings through the use of driver-infrastructure interfaces (e.g., dynamic signs) and driver-vehicle interfaces (e.g., dashboard displays). The team explored concepts like left hand turn assistance, “all-red” clearance for side collision avoidance, red light running, and pedestrian crossing detection. All of these are relevant to ATTRI stakeholders as intersection navigation, both by cars and pedestrians, can be particularly challenging for busy intersections. Also, many ATTRI stakeholders lack the perception ability or reaction time necessary to execute emergency maneuvers, either while driving or as pedestrians. Therefore, they are more likely to experience a collision when others would experience a near miss.

3.4.3.3 Vehicle to Pedestrian

One of the most promising DSRC functionalities for ATTRI stakeholders is communication between vehicles and pedestrians to help avoid collisions. Roadside infrastructure is unlikely to be in all locations, especially in suburban communities and mid-block areas. People with shorter stature due to height or wheelchair use are also at risk near residential driveways and in parking lots. Therefore, the ability to issue collision warnings directly between vehicles and smartphones has significant potential to reduce risk among ATTRI pedestrians. Likewise, ATTRI drivers may have reduced situation awareness for the rear and sides of their vehicles due to perceptual and neck motion impairments. Xu, et al (2015) describes a prototype system of this type and demonstrates use in clear line of sight and non-line of sight scenarios. Alerts were displayed for both the driver and pedestrian. A similar system is under development by Savari under an SBIR project (Transportation.gov, 2015).

The next obvious step is to move from warning to avoidance. In this case, the vehicle could automatically stop to avoid collisions with pedestrians. This would likely require some data fusion where communicated location data was merged with vehicle sensor data, thus limiting the likelihood of false alarms and unnecessary stops.

3.4.3.4 Intersection Technology

Several research teams have explored ways for intersections to warn pedestrians to potential threats (e.g., California PATH, 2011). The core idea centers on intersections comparing signal phase and timing with trajectories of pedestrians to infer risk. This assumes good detection and tracking of pedestrians by the intersection. The CICAS project (Misener, et al 2010) utilized extensive technology infrastructure for coordination, communication, and sensing. The latter is important when trying to detect and track vehicles and pedestrians that are not equipped with DSRC or similar communication systems. It is highly likely that market penetration for such devices will be slow and uneven within the ATTRI population. Those with financial resources are likely to consider equipped smartphones or beacons while many others will lack the motivation or finances to acquire a device. Therefore, use of intersection-based sensing systems will be necessary for some time. Of these, computer vision is likely to have the best performance due to the wide field of view, low power, and low cost in comparison to other sensors. Discussion of computer vision perception occurs earlier in this document.

3.4.3.5 Roundabout Technology

Technologies for safer traversal of roundabouts by people with disabilities have been identified as a research gap for pedestrians since they often lack adequate knowledge of driver intentions (Morton and Yousuf, 2011). This remains a largely untapped research area and literature on technology for this topic is sparse. Pedestrian oriented approaches are generally focused on low technology solutions, like mixing signal lights with roundabouts or using grade separation.

3.4.4 First / Last Mile

There is interest within the international community to facilitate rider information for jitneys and other short hop services. Current approaches focus on motivating and enabling service providers to create GTFS data files for scheduled routes and trips (e.g., Krambeck, 2012). This will allow trip planners to incorporate these services into multimodal routes.

3.4.5 Pedestrian

Interesting functionality can be achieved by integrating data from pedestrian smartphones with the local environment (e.g., traffic signal phase, elevator call, etc). The proliferation of smartphones combined with rich sensor suites allow novel concepts to be explored. Since commercial smartphones currently do not have DSRC, most research teams have explored other communication methods. Research teams have explored concepts like tailored interaction with nearby infrastructure to trigger infrastructure actions, characterize routes, and convey information to the user (e.g., Vales-Alonso, et al 2008; Mirri, et al 2014).

3.5 Enhanced Human Service Transportation

As we saw in the **[SOP]** and **[INNO]** documents, there is a convergence of EHST assistance towards more flexible and accurate transportation scheduling, easier interregional fare payment, better incentives to familiarize persons with the benefits of using fixed route transit, and additional modes that address first / last mile challenges. These pressures are more prevalent for veterans with disabilities and older adults than they are for other persons with disabilities. Housing for veterans is often located in rural areas where land is inexpensive with respect to the urban areas that are served by main line and fixed route transit. Many older adults are aging in place and living in the suburbs and rural areas where they were in the habit of driving a personal vehicle as their primary mode of transportation. Unfortunately, individuals of both groups may find that they cannot travel by personal vehicle and must rely on alternative mode options. Hence the research technologies that will be highlighted in this section will focus on this challenge.

Cross-cutting research technologies that we identified pertain to encouraging older adults to use fixed-route transit when they had limited familiarity with transit. The most important EHST transit research technology is that of on-demand and flexible scheduling, which applies to paratransit as well as transit services for sparsely populated rural areas or assisted living and veterans communities. This includes consideration of the use of taxis and shared vehicles in rural areas since there is not a density of supply and demand to maintain the economies of scale of traditional ride for hire business models.

3.5.1 Cross-Cutting

Fostering healthier and more sustainable travel mode choices is attractive to many governments for a variety of macroeconomic reasons. Research teams have been exploring how to use newer technologies to motivate such choices within the general public, either through gamification, context-aware computer recommendations, or interaction design. For example, van Amelsfort, et al (2014) describes an approach where commuters receive points for avoiding rush hour or selecting more sustainable transportation options. The team increased motivation by allowing accumulated points to be exchanged for money. The approach was successful but some participants did not alter travel behavior and some dropped out of the study after receiving initial financial rewards. It is also important to design incentives properly since some pedestrian commuters switched to transit due to the way points were awarded. This is counter-productive for those who need the exercise.

User design profiles are a common technique when attempting to design new experiences and systems. The GOAL project (Hoedemaeker, 2013) examined older populations across Europe to craft five senior profiles, some of which include people with disabilities. These profiles were driven by the intersection of age and the combination of activity level and health, which are typically highly correlated. Profile group names include: Fit as a Fiddle, Happily Connected, An Oldie but Goodie, Hole in the Heart, and the Care-Full. The project final report includes group population forecasts and technology need predictions.

3.5.2 Transit

As mentioned above, the greatest challenges to veterans with disabilities and older adults are related to the availability and flexibility by which transit can be scheduled. As we have seen in the **[SOP]** and **[INNO]**, the scheduling of transit requires considerable advanced notice, artificially long estimated transit duration times to allow for changes to the schedule, and long lapses in the pickup of the individual from their destination at the end of their appointment. This section, therefore, considers two significant areas of research: (1) scheduling paratransit and (2) vehicles for on-demand hire, such as taxis and shared vehicles.

3.5.2.1 Paratransit

In his literature review, Quadrifoglio (2013) characterizes the paratransit scheduling problem as the *dial-a-ride problem (DARP)*, which in turn, is a mixture of other well-known research problems: the *pick-up and delivery problem (PDP)*, and the *traveling salesman problem (TSP)*. The author considers each of these strategies in a federated centralized model, called zoning, as well as a in a decentralized model of scheduling dispatch. The literature review also discusses prior work in estimating savings by coordinating services across paratransit zones.

The REVAMP (REal-time Vehicle Allocation application for increased Mobility in Paratransit operations; 2015) project is an attempt to improve this dispatching process through a mixed-initiative, dynamic scheduling. It receives real-time status and location information from the vehicles in the field and maintains a “live” schedule that is constantly updated to reflect what actually happens during execution. This active model provides paratransit dispatchers with better situational awareness of the states of current and future trips. For trips that are in jeopardy of having a poor quality of service, REVAMP can detect them and provide dispatchers with options for rerouting them to improve their quality of service.

The system is designed to incrementally accept real-time updates of vehicle status, and provide the dispatcher with a live schedule that continually reflects the current execution state. Since this schedule encodes all relevant constraints and requirements (e.g., expected travel durations, negotiated pick-up times, maximum transit time limits), one immediate benefit is the early detection and alerting of emerging problems (e.g., given the customer pick-up that was just reported, the next scheduled pick-up after this current trip is projected to be beyond its acceptable window). This capability alone affords the dispatcher with more time to take corrective action, and in the worst case, enables the dispatcher to inform customers in advance of unavoidable delays. To support dispatcher response to detected problems, REVAMP is designed to generate options for rearranging trips across vehicles to minimize the impact on customer quality of service. This same option generation mechanism can also be used as the means for improving the efficiency of vehicle itineraries when opportunities arise (e.g., trip cancellations) and for accommodating new requests that arrive dynamically through the day (e.g., “will call” return trips).

To ensure proper travel durations, REVAMP adjusts the travel durations of constituent tasks where necessary (e.g., rush hour) after any change is made to a vehicle timeline. The system also tracks actual start and finish times to determine if REVAMP should alert the human dispatcher of trips that are likely to violate the service constraints. The dispatcher can also view all endangered trips, along with the expected magnitude of delay in each case. Early testing of REVAMP successfully showed the feasibility of the approach but it has not been adopted yet due to integration issues.

3.5.2.2 Taxis and Shared Vehicles

There are many advances in on-demand for hire services (see **[INNO]**) but long-term technology advances center on autonomous vehicles. Uber’s interest in autonomous vehicles raises obvious opportunities regarding service delivery, cost, and other societal factors. First and foremost is the possibility for greater service area coverage and density. With the costs and logistics associated with drivers no longer present, it becomes possible to scale-up. Current taxi drivers optimize their strategies for personal gain while a driverless system could be optimized for societal gain. This could lead to better coverage and service in areas that typically lack high value rides. Another important element is the ability to use vehicle designs that are more open and easier to board. Removing the driver seat supports new, innovative vehicle designs.

Aside from the promise of greater independence for those who cannot drive due to ability or cost, the full potential of shared, driverless electric vehicles are likely to have a significant positive impact on sustainability and cost (Burns, et al 2013). Estimates on the savings from even a modest impact in the United States are upwards of $50 billion per year (Burns 2013). One of the interesting nuances is lower cost for travel at the individual level. One study on the hypothetical impact of autonomous dynamic ride-sharing for Austin, Texas showed that a taxi operator could earn a 19% annual long-term return while charging $1.00 per mile for non-shared trips (Fagnant and Kockelman, 2015). The authors note this is one third of the current fare charge in this city. Cost savings are very important for many ATTRI stakeholders who are retired, unemployed, or underemployed.

3.5.3 Personal Vehicles

Policy will have a very important influence on service models for autonomous taxi, shared vehicle, or personal vehicles. Most current policies either require a licensed driver behind the wheel of the car or are leaning in that direction. This, obviously, creates problems for ATTRI stakeholders who cannot drive since many service models with the promise of greater independence cannot meet this requirement.

The above studies on autonomous taxis and shared vehicles work from the position that each car will be used by more than one person throughout the day. This may not be the case everywhere, which could lead to unintended consequences. One study explored the impact of autonomous driving by seniors and people with disabilities who are currently unable to drive and found overall vehicle miles traveled could increase by 12% due to newfound travel independence (Harper, et al 2015). This is clearly undesirable for many economic, congestion, and sustainability reasons. Therefore, multi-user service models for autonomous vehicles are likely to be important.

3.5.4 First / Last Mile

Research has shown that seniors are more likely to stop driving when transportation support is available, even if trips are provided by friends or hired assistants (e.g., Choi, et al 2012). This suggests a rich opportunity for taxi, TNC, and dynamic ridesharing modes for helping senior drivers make safer choices when deciding to stop driving. There is already evidence that TNCs lead to safer driving choices in regards to drunk driving (UBER and MADD, 2015), so a similar effect may be seen in seniors as they become familiar with newer transportation options. This may also lead to use of TNCs and dynamic ridesharing for first / last mile travel, especially in suburbs and other regions where driving one’s own vehicle is the only attractive option due to poor taxi coverage and sparse transit stops.

3.5.5 Pedestrian

There is ongoing research on walking tools and walkability scores. The former are designed to promote walking among seniors and remove some of the uncertainty of pedestrian travel (e.g., Fan, et al 2012) since some environmental perceptions are associated with specific walking behaviors (Maisel, 2014). These are similar to aforementioned work on crowdsourcing pedestrian route information (Jonnalagedda, et al 2014; Min, et al 2015a).

Walkability scores are attractive to urban planners and sustainability experts since they help characterize the ease of pedestrian travel in quantifiable form (e.g., Chen, et al 2015). Some of these methods utilize inputs important to ATTRI stakeholders but may not weight inputs appropriate to their needs. For example, they may discount paths that traverse steps in comparison to hills or ramps. Thankfully, some teams are explicitly modeling ATTRI stakeholders (e.g., Sharifi, et al 2015).

4 Recommendations for Phase 2 Utilization

The intent of this section is to identify candidate technological advances and service insights that, if promoted and stimulated through appropriate levels of research, development, and evaluation, would contribute significantly to enabling greater transportation independence for ATTRI stakeholders.

The recommendations are organized according to each of the five ATTRI-identified technology areas. By virtue of transportation systems being socio-technical systems that involve synergistic cooperation among both autonomous and human systems, special attention must be provided to ensure that key stakeholders are identified, involved and engaged as active participants in any proposed solution throughout its lifecycle.

Note that the recommendations are the opinions of the authors and not the Federal government.

4.1 Wayfinding and Navigation

The primary challenge of wayfinding and navigation for persons with disabilities is that of acquiring and using good maps and associated data. Maps should support reasoning during wayfinding and navigation tasks for both people and automation. Maps are only as accurate and reliable as the processes that created and maintained them. In order for wayfinding and navigation technologies to be used effectively in end-to-end transportation applications, maps should also support integration with additional information and annotations of relevance to: points of interest, outdoor spaces (e.g. roadsides, sidewalks, courtyards, parking lots, transit stops and approaches to transit stations, etc.), spaces within vehicles, and spaces within buildings of all purposes and designs. Finally, traditional map reasoning tools are good, but often lack functionality useful for ATTRI stakeholders. For example, a routing tool may provide options for quickest route or least transfers, but none include options like smallest crowds, quietest route, or the availability of service personel. Therefore, the recommendations for wayfinding and navigation are:

- **Integration of Map Data from Various Sources.** Aside from regular digital map data, relevant information includes methods for easily integrating location-specific data from other sources, like reading the location of a bus stop and which routes arrive there from an external GTFS source. Since these maps are likely to be used by many, they should be accessible for third party developers via open data and open services models. There already exist large, rich mapping efforts within industry so building the underlying digital map data is likely to be inefficient. Instead, efforts should be focused on how to make these maps better and more useful to the ATTRI developer community. Research is needed on how to bridge gaps between different map databases for easier and better integration. For example, one map database may assign a precise GPS descriptor for a bus stop while a different database may just say curb cuts are present at an intersection.

- **Infrastructure Descriptions.** While there are many methods for documenting building structures and features, there are some infrastructure elements which have a strong impact on ATTRI stakeholders that need standardized encoding methods. For example, teams are gathering data on the presence of stairs or the quality of sidewalks but lack standardized descriptions for sharing with others. Inconsistencies will make scalable, nationwide products difficult to achieve.
- **ATTRI Specific Data.** While there is a lot of useful data in existing map systems, they often lack critical data relevant to ATTRI stakeholders. For example, a Points of Interest database may give the location of a store, but not where the entry door is, whether there are steps at the door, or if a restaurant has an accessible bathroom. It is possible to look for this in tools like StreetView or to call the store phone number, but this information is not machine-readable, so it is hard for navigation tools to know these details.
- **Universal Indoor Localization.** While there has been regular and steady improvement in low cost localization in GPS-denied regions, advances in wayfinding and navigation continue to be constrained by technology and institutional barriers. Infrastructure based approaches (e.g., Bluetooth beacons) will likely require a universal design approach due to deployment costs and other barriers. Likewise, good localization is valuable to people with varying disabilities so a universal approach will lower barriers for multiple user groups.
- **Accessible Personal Interfaces.** New ATTRI applications developed for smartphones and wearable electronics need to be accessible. Ideally, these applications will embody universal design principles to enable broader use.

Wayfinding and Navigation Stakeholders: ATTRI Stakeholder Groups, transit operators, building managers, POIs, trusted sources such as caregivers and mobility instructors.

4.2 ITS and Assistive Technologies

Uncertainty is a major problem for ATTRI stakeholders and the small market problem for assistive technologies leads to greater risk of disrepair or lack of training. There are many interesting and useful systems in use, but the service breakdowns and maintenance issues create problems for those who depend on them. These lead to the first two recommendations for this category:

- **Modernized Maintenance and Asset Management.** Applying ITS approaches to assistive technology maintenance and asset management is a rich area for advancement. For example, real-time information about vehicle lift or elevator state of repair should be easily shared with transit information apps.

- **Remote assistance.** Economic pressures on transportation providers create problems in cases where local staffing is not economically feasible. This goes beyond simple voice calls and includes the ability of remote service providers to actuate local assistive technologies and infrastructure. At the simplest level, transit agency staff should be able to control specific fare gates, doors, and elevators remotely so ATTRI stakeholders do not have to wait for service. Advanced remote assistance, like moving a robotic ramp or lift into place for grade changes between platforms and trains, should also be considered.

Grade changes and poor sidewalk surfaces are (unfortunately) prevalent and spending on infrastructure is generally down. A single missing curb cut can move a fixed-route rider to paratransit. Likewise, uncleared snow and ice on sidewalks can push transit riders who are blind into paratransit or suppress overall travel. This leads to the next recommendation:

- **Barrier Traversal.** Better assistive technology for managing curbs and sidewalk barriers are often necessary. Grade change barriers impact access to many places of employment, retail, and residences are present due to cost of modification and other reasons. The Veterans Administration has made progress on these issues through novel wheelchair designs, so this may be an opportunity for collaboration. Robot movement over poor terrain is also a topic that is heavily researched by the Department of Defense. Similar systems could also be used to facilitate snow and ice removal, when necessary.

ITS and Assistive Technology Stakeholders: ATTRI Stakeholder Groups, transit operators, municipalities, assistive technology manufacturers.

4.3 Automation and Robotics

Military bases, senior communities, and suburban regions all create barriers to transportation independence due to the inherent distances between transit stops, homes, and places of employment. Autonomous personal vehicles are likely to be far beyond the finances of most ATTRI stakeholders, thus leading to the following recommendation:

- **Shared Neighborhood Autonomous Vehicles.** The efforts of ARIBO and CityMobil2 are an excellent start but more research in this space is needed due to the size and severity of the first / last mile problem within the United States. Vehicles of this type have significant promise in resolving first / last mile access to employment and residences, so more research on this topic is needed. In particular, solutions that do not require a driver's license for operation are necessary.
- **Accessible Vehicles.** Unfortunately, most vehicles on the road are not inherently accessible. This limits the ability to independently board autonomous vehicles or ride in transportation network company (TNC) or taxi vehicles. Seamless vehicle boarding and egress is necessary to fully realize the potential of these services. Car sharing service models, electric vehicles, and autonomous vehicles create opportunities for novel

vehicle design. Advances on this issue will be especially important for access to healthcare and employment in areas not well served by transit or pedestrian alternatives. The ability to enter a passenger vehicle from a suburban or rural location is also important for people aging in place.

Advances in robotics are also ready for translation to ATTRI systems. This is especially true for computer vision and activity prediction, which is the basis for the next recommendation:

- **Look Ahead Functions.** Navigation and routing that do not predict upcoming changes in the environment will inherently produce reactive behaviors. A system that does not infer how the user and other parties move and act will inadvertently create problems. Users do not want to be led into dangerous areas or be perceived as rude by bystanders. Prediction also enables more appropriate infrastructure decision-making, better autonomy, and overall safety. Research is needed on how to provide this kind of forward looking, socially aware guidance.

Automation and Robotics Stakeholders: ATTRI Stakeholder Groups, transit operators, municipalities, OEMs, suppliers, and system integrators.

4.4 Data Integration

Data integration is an enabling technology for a variety of ATTRI applications. While general advances are occurring as a result of popular topics like artificial intelligence and big data, focused attention is needed on ATTRI-specific gaps. Recommendations include:

- **Open Data and Open Services.** Continuing the trend of open data provided by municipal services and information sources will be important for scaling ATTRI solutions across the country. Open services, where code and data is private but usable by third parties through easily coded software tools (e.g., Google Maps API), will also be important for accelerating development of novel ATTRI systems. This recommendation aligns with Smart Cities efforts and Internet of Things applications, thus illustrating the importance of coordination on standards with related efforts.
- **Connectivity.** Early research on wireless connectivity between ATTRI stakeholders and other transportation elements has demonstrated safety and convenience. Continued effort is needed in this area, especially for applications for personal connectivity. Functionality like alerting for pedestrian-vehicle collsions and relaying information about bus route numbers can be more effective and timely with connectivity. Universal design is important due to market forces and deployment barriers. Therefore, systems should utilize mainstream connectivity methods.
- **Machine Readable Personal Profiles.** Since ATTRI stakeholders have significant variability in needs and capabilities, it will be important to encode individual preferences on how service and technology should be used. For example, a scooter user may be willing and able to walk out of a train or airplane to meet their scooter at the platform or

gate. Requiring them to wait for a transfer chair or lift that is 20 minutes away is counterproductive. Likewise, some databases merely indicate the traveler is disabled, rather than specific needs, thereby leading to provision of the wrong service or technology. In some cases, these profiles could be learned from direct interaction with the user or caregiver. The location and access to these profiles is an open question but it will be necessary to preserve privacy so profiles are not used improperly.

- **Service Matchmaking.** Some ATTRI stakeholders have access to services limited to their population group (e.g., senior discounts, military transportation, etc). In other cases, caregivers may wish to limit which transportation services are offered as a means of reducing complexity or exposure to danger. Automated methods for filtering, identifying, and surfacing the right transportation options to users will be important. This includes the option to do hypothetical planning since awareness and easy utilization of transportation services can positively impact employment opportunities and access to healthcare.
- **Community Generated Data.** Existing research has shown that members of the community, including those who are not ATTRI stakeholders, are more than willing to provide knowledge and expertise in transportation systems. Research has also shown such contributions can be very effective in bridging accessibility gaps. Unfortunately, many crowdsource systems fail over time for a variety of reasons, thus suggesting that new models for generalizable approaches are needed. Research is needed on how to motivate and sustain these communities as well as how to use such contributions to better support independent travel by ATTRI stakeholders.

Certain map data integration technologies have already been described above and are relevant beyond just wayfinding and navigation.

Data Integration Stakeholders: ATTRI Stakeholder Groups, government agencies, software companies, and system integrators.

4.5 Enhanced Human Service Transportation

There are many new and possibly useful service models in use today. Unfortunately, little is known about their long-term potential and impact with respect to ATTRI stakeholders. Further research is necessary, particularly through field tests and stakeholder input, to identify and explore how these systems can have positive impacts on ATTRI stakeholders. Therefore, research is needed on:

- **TNCs and Ridesharing.** Initiatives by TNCs to involve ATTRI stakeholders are an opportunity to better understand how accessible versions of these services can positively impact travel independence. Research on existing programs like UberMILITARY and the use of accessible vehicles by TNCs are opportunities to obtain rapid insight on these trends. Likewise, many government agencies are interested in how to ensure equal access for people with disabilities within these service models. TNCs are also an attractive employment option for ATTRI stakeholders. Due to all of these questions, there is a need to better understand how TNCs and ridsharing technologies can transport and employ ATTRI stakeholders.

- **Mode Shifting.** The oncoming age wave and long-term focus on suburban planning within the United States will be increasingly problematic as seniors transition out of driving. Neighborhood autonomy and private on-demand ride services may help mitigate this looming problem, but it will also be important to support and encourage shifts to non-driving modes. This will likely require a variety of technologies and services designed to coach users through unfamiliar transportation systems, inform users of options in easy to understand ways, and act as a guardian angel in order to detect and warn users when they are about to make a mistake (e.g., take an outbound train instead of an inbound one). Caregiver tools for remote support are also relevant.

Enhanced Human Service Transportation Stakeholders: ATTRI Stakeholder Groups, government agencies, EHST service providers, and system integrators.

Specific products identified in the recommendations or in the document are not endorsments. 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.

5 Conclusions

There are many promising and interesting research efforts underway relevant to the transportation needs of ATTRI stakeholders. In many cases, these research efforts center on the functional areas of mobility and vision. This is not surprising since barriers in these functional areas can completely prevent independent travel and people with these disabilities are “visible” to technology developers and service providers.

An example of this bias is the glaring, repeated absence within the transportation research space of projects focused on the hearing functional area. Such barriers are often limited to specific challenges, like airport announcements. To some degree, barriers for people who are deaf or hard of hearing can be addressed with existing best practices (e.g., captioning on terminal screens of announcements) and diligent service (e.g., attentive gate agents). Likewise, research efforts on accessible computing, hearing enhancement, and other general purpose areas can address technology gaps within transportation. Funding sources and peer review panels are aware of this context and therefore tend to not fund transportation research projects in this functional area. Focused research in this functional area may be necessary if user needs assessments reveal gaps that cannot be met through traditional technologies and customer service. Regardless of whether research in this area is funded, it is imperative that interfaces for ATTRI technologies be accessible to people who are deaf or hard of hearing.

Similarly, the cognitive functional area has seen some research effort but is in dire need of more advances. The lack of attention may be partially due to the technical challenge of serving this population. Technology is generally better at performing mobility and perception tasks than cognition. The recent research boom in artificial intelligence and machine learning should lead to new research and technologies in support of the cognitive functional area. Therefore, it is reasonable to expect accelerated growth in this area in the near future.

The recommendations in this document were intentionally selected for their potential for deployability over the near term but some longer-term research was included, where appropriate. While some of the recommendations have prior work demonstrating some value, few have shown this on a large scale in the real world. Therefore, there is an overarching research need to evaluate the impact of future systems on the daily lives of ATTRI stakeholders.

6 References

Aalto University (2015). Work Partner. http://autsys.aalto.fi/en/WorkPartner

Accessible Transportation Technologies Research Initiative (ATTRI) Institutional and Policy Issues Assessment, Task 6: Summary Report FHWA-JPO-17-506.

Ackerman, E. (2014). Hyundai Robocar Competition: KAIST Details Weather Problems, Philosophical Differences. IEEE Spectrum: Cars That Think. http://spectrum.ieee.org/cars-that-think/transportation/advanced-cars/kaist-describes-weather-problems-philosophical-differences-in-autonomous-vehicle-competition/?utm_source=carsthatthink&utm_medium=e

Aethon (2015). Tug. http://www.aethon.com/tug/benefits/

Alber (2015). Scalamobil. http://www.alber.de/en/products/the-mobile-stair-climber/stair-wheelchair-scalamobil.html

Asakawa, C. (2015). How new technology helps blind people explore the world. TED. https://www.ted.com/talks/chieko_asakawa_how_new_technology_helps_blind_people_explore_the_world

ATR (2015). Ubiquitous Network Robot. http://www.irc.atr.jp/en/research-projects/unr/

Babcock Ranch (2015). All systems go for Babcock Ranch. https://www.babcockranchflorida.com/blog/all-systems-go-for-babcock-ranch

Baker, S. Zhong, V., Hsu, J., Macchi, P., Kimmel, S., Gladysz, L., Yousuf, M., Groudine, C., & Wood, K. (2017). Accessible Transportation Technologies Research Initiative (ATTRI) Institutional and Policy Issues Assessment, Task 6: Summary Report FHWA-JPO-17-506. USDOT.

Barabino, B., Casari, C., Demontis, R., Lai, C., Mozzoni, S., Pintus, A., & Tilocca, P. (2014). A web platform for user-oriented reliability diagnosis in bus transit services. Proceedings of the ITS World Congress.

Barry, K. (2011) High-Tech Car Allows the Blind to Drive. Wired. http://www.wired.com/2011/02/high-tech-car-allows-the-blind-to-drive/

BestMile (2016). BestMile. https://bestmile.com

6 References

Bhatlawande, S., Mahadevappa, M., & Mukhopadhyay, J. (2013). Way-finding Electronic Bracelet for visually impaired people. In IEEE Point-of-Care Healthcare Technologies (PHT). http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=6461334&tag=1

Bhatlawande, S., Sunkari, A., Mahadevappa, M., Mukhopadhyay, J., Biswas, M., Das, D., & Gupta, S. (2014). Electronic Bracelet and Vision-Enabled Waist-Belt for Mobility of Visually Impaired People. Assistive Technology, 26(4), 186-195.

Bilmes, L. (2007). Soldiers Returning from Iraq and Afghanistan: The Long-term Costs of Providing Veterans Medical Care and Disability Benefits. Kennedy School of Government, Harvard University. http://papers.ssrn.com/sol3/papers.cfm?abstract_id=939657

Blind Driver Challenge (2015). Blind Driver Challenge. http://www.blinddriverchallenge.org

BLS (2014). Current Population Survey (CPS). U.S. Department of Labor, Bureau of Labor Statistics. http://www.bls.gov/cp

Boston Dynamics (2015). LS3 - Legged Squad Support Systems. http://www.bostondynamics.com/robot_ls3.html

Brakewood, C., Barbeau, S., & Watkins, K. (2014). An experiment evaluating the impacts of real-time transit information on bus riders in Tampa, Florida. Transportation Research Part A: Policy and Practice, 69:409-422. http://dx.doi.org/10.1016/j.tra.2014.09.003

Brault, M. W. (2012). Current Population Reports. Americans with Disabilities 2010. U.S. Census Bureau. http://www.census.gov/prod/2012pubs/p70-131.pdf

Bridj (2015). Bridj. http://www.bridj.com

Brooks, D. (2015). Driverless cars in the near future for Fort Bragg. Fayetteville Observer. http://www.fayobserver.com/news/local/driverless-cars-in-the-near-future-for-fort-bragg/article_9ab20600-c91a-5360-b1a4-be8bcc90dce1.html

Burkhardt, J. E., Rubino, J. M., & Yun, J. (2011). Improving Mobility for Veterans. Transit Cooperative Research Program Research Results Digest 99. Transportation Research Board. http://onlinepubs.trb.org/onlinepubs/tcrp/tcrp_rrd_99.pdf

Burns, L. D. (2013). Sustainable mobility: A vision of our transport future. Nature, 497:181-182.

6 References

Burns, L. D., Jordan, W. C. & Scarborough, B. A. (2013). Transforming Personal Mobility. Earth Institute, Columbia University. http://sustainablemobility.ei.columbia.edu/files/2012/12/Transforming-Personal-Mobility-Jan-27-20132.pdf

California PATH. (2011). Investigating the Potential Benefits of Broadcasted Signal Phase and Timing (SPaT) Data under IntelliDrive(sm), Final Report. http://www.cts.virginia.edu/wp-content/uploads/2014/04/PFS_SPAT99_Final.pdf

CATT Lab (2015). Portfolio. http://www.cattlab.umd.edu/?page_id=17

Census (2012). Facts for Features: Older Americans Month: May 2012. U.S. Census Bureau. https://www.census.gov/newsroom/releases/archives/facts_for_features_special_editions/cb12-ff07.html

Chaki, S., & Giampapa, J. A. (2013). Probabilistic Verification of Coordinated Multi-Robot Missions. In Model Checking Software (Ezio Bartocci and C.R. Ramakrishnan, ed.). pp. 135-153. Berlin: Springer. http://www.ri.cmu.edu/publication_view.html?pub_id=7595

Chaki, S., Dolan, J. M., & Giampapa, J. A. (2013) Toward a Quantitative Method for Assuring Coordinated Autonomy. Proceedings of the AAMAS Workshop on Autonomous Robots and Multirobot Systems (ARMS). http://www.ri.cmu.edu/publication_view.html?pub_id=7608

Chang, Y. J., Tsai, S. K., & Wang, T. Y. (2008). A context aware handheld wayfinding system for individuals with cognitive impairments. In Proceedings of the International ACM SIGACCESS Conference on Computers and Accessibility (ASSETS). http://doi.acm.org/10.1145/1414471.1414479

Chen, W.-H., Lin, W.-I., Chang, S.-H., & Mak, L.-C. (2015). Exploring the Relationships Between the Physiological and Psychological Condition of Seniors and Their Mobility and Social Activity. Transportation Research Board 94th Annual Meeting. http://trid.trb.org/view.aspx?id=1337054

Cho, H., Rybski, P. E., & Zhang, W. (2010). Vision-based bicyclist detection and tracking for intelligent vehicles. IEEE Intelligent Vehicles Symposium.

Choi, M., Adams, K. B., & Kahana, E. (2012). The impact of transportation support on driving cessation among community-dwelling older adults. Journals of Gerontology Series B: Psychological Sciences and Social Sciences, 67B(3), 392-400.

CityMobil2 (2015). CityMobil2. http://www.citymobil2.eu/en/

Cooper, R. A., Grindle, G. G., Vazquez, J. J., Xu, J., Wang, H., Candiotti, J., Chung, C., Salatin, B., Houston, E., Kelleher, A., Cooper, R., Teodorski, E., & Beach, S. (2012). Personal Mobility and Manipulation Appliance - Design, Development, and Initial Testing. Proceedings of the IEEE, 100(8), 2505-2511. http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6218156&isnumber=6239645

Coughlan, J. M., & Shen, H. (2012). The crosswatch traffic intersection analyzer: a roadmap for the future. Computers Helping People with Special Needs, Lecture Notes in Computer Science, 7383:25–28.

C-Ride (2015). Connect and Ride. http://www.connectandride.com

D'Souza, C. (2013). Usability and Person-Environment Interaction in Constrained Spaces: Wheeled Mobility Users and Interior Low-Floor Bus Design. Unpublished doctoral dissertation. Department of Industrial and Systems Engineering. State University of New York at Buffalo, Buffalo, NY.

Darms, M. S., Rybski, P. E., Baker, C., & Urmson, C. (2009). Obstacle Detection and Tracking for the Urban Challenge. IEEE Transactions on Intelligent Transportation Systems, 10(3), 475-485.

Davidoff, S., Ziebart, B. D., Zimmerman, J. & Dey, A. K. (2011). Learning Patterns of Pick-ups and Drop-offs to Support Busy Family Coordination. SIG CHI Conference on Human Factors in Computing Systems (CHI). http://www.cs.uic.edu/pub/Ziebart/Publications/learning-patterns-pick-ups.pdf

Dias, M. D. (2015). The NavPal Suite of Tools for Enhancing Indoor Navigation for Blind Travelers. In Indoor Wayfinding and Navigation (H. A. Karimi, ed). pp. 187–202. CRC Press. http://www.crcnetbase.com/doi/abs/10.1201/b18220-10

EAR (2015). Assistive Technologies for Visually Impaired Persons. The Exploratory Advanced Research Program Fact Sheet, FHWA-HRT-15-040 HRTM-30/02-15(1M)E.

Erikson, W., Lee, C., & von Schrader, S. (2014). 2012 Disability Status Report: United States. Employment and Disability Institute, Cornell University.

Fagnant, D., J., & Kockelman, K. M. (2015). Dynamic Ride-Sharing and Optimal Fleet Sizing for a System of Shared Autonomous Vehicles. Proceedings of the Annual Meeting of the Transportation Research Board. http://www.ce.utexas.edu/prof/kockelman/public_html/TRB15SAVswithDRSinAustin.pdf

6 References

Fan, C., Forlizzi, J., & Dey, A. (2012). Considerations for Technology that Support Physical Activity by Older Adults. In Proceedings of ACM SIGACCESS Conference on Computers and Accessibility.

Farran, Emily K., Courbois, Yannick, Van Herwegen, Jo, and Blades, Mark, (2012B). "How useful are landmarks when learning a route in a virtual environment? Evidence from typical development and Williams syndrome," in Journal of Experimental Child Psychology, 4(111), 571-586, doi 10.1016/j.jecp.2011.10.009, 2012.

Farran, Emily K., Courbois, Yannick, Van Herwegen, Jo, Cruickshank, Alice G., and Blades, Mark, (2012A). "Colour as an environmental cue when learning a route in a virtual environment: Typical and atypical development," in Research in Developmental Disabilities, 3(33), 900-908, doi 10.1016/j.ridd.2011.11.017, 2012.

Ferlis, R. A. (2007). The Dream of an Automated Highway. Public Roads, 71(1). FHWA-HRT-07-005. Federal Highway Administration. http://www.fhwa.dot.gov/publications/publicroads/07july/07.cfm

Ferris, B., Watkins, K., & Borning, A. (2010). OneBusAway: Results from providing real-time arrival information for public transit. Proceedings from the International Conference on Human Factors in Computing Systems (CHI). http://dl.acm.org/citation.cfm?id=1753597

Galatas, G., McMurrough, C., Mariottini, G. L., & Makedon, F. (2011). eyeDog: an assistive-guide robot for the visually impaired. In Proceedings of the 4th International Conference on PErvasive Technologies Related to Assistive Environments.

Galatas, G., McMurrough, C., Mariottini, G. L., & Makedon, F. (2011). eye-Dog: An Assistive-guide Robot for the Visually Impaired. Proceedings of the International Conference on Pervasive Technologies Related to Assistive Environments.

Garaventa (2015). Portable Wheelchair Lifts. http://www.garaventalift.com/en/products/wheelchair-lifts/portable-wheelchair-lifts.html

Gardiner, S., Tomasic, A., & Zimmerman, J. (2015). SmartWrap: seeing datasets with the crowd's eyes. In Proceedings of the 12th Web for All Conference (W4A '15). http://doi.acm.org/10.1145/2745555.2746652

Gardiner, S., Tomasic, A., Zimmerman, J., Aziz, R., & Rivard, K. (2011). Mixer: mixed-initiative data retrieval and integration by example. Proceedings of the IFIP TC 13 International Conference on Human-computer Interaction (INTERACT). http://dl.acm.org/citation.cfm?id=2042053.2042099

6 References

Giampapa, J. A., & Sycara, K. (2001). Conversational case-based planning for agent team coordination. In Case-Based Reasoning Research and Development: Proceedings of the Fourth International Conference on Case-Based Reasoning (pp. 189-203). Springer Berlin Heidelberg.

GoMentum Station (2016). Autonomous Vehicle (AV) Program. http://gomentumstation.net/project/av/

Gonzalez, A., Bergasa, L. M., Yebes, J. J, & Almazan, J. (2012). Text recognition on traffic panels from street-level imagery. IEEE Intelligent Vehicles Symposium (IV). http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6232157&isnumber=6232109

Google (2012). Self-Driving Car Test: Steve Mahan. Youtube. https://www.youtube.com/watch?v=cdgQpa1pUUE

Google (2014). A First Drive. Youtube. https://www.youtube.com/watch?v=CqSDWoAhvLU

Google (2015). Google Self-Driving Car Project. http://www.google.com/selfdrivingcar/

GTFS-SUM (2015a). What is GTFS-SUM ? Technical Brief / Concept Paper. https://gtfssum.wordpress.com/2015/06/22/what-is-gtfs-sum/

GTFS-SUM (2015b). GTFS-SUM Roadmap, http://gtfssum.com

Gu, Y., Yendo, T., Tehrani, M. P., Fujii, T., & Tanimoto, M. (2010). A new vision system for traffic sign recognition. IEEE Intelligent Vehicles Symposium.

Guentert, M. (2011). Improving public transit accessibility for blind riders: a train station navigation assistant. In Proceedings of the International ACM SIGACCESS Conference on Computers and Accessibility. http://dl.acm.org/citation.cfm?id=2049626

Hachman, M. (2012). Police: Blind Driver's Trip in Google's Self-Driving Car Was Legal. PCMag.com. http://www.pcmag.com/article2/0,2817,2402380,00.asp

Hall, Z., Kazman, R., Plakosh, D., Giampapa, J. A., & Wallau, K. (2010). Edge Enabled Systems. Armed Forces Communications and Electronics Association (AFCEA) - SOLUTIONS Series George Mason University Symposium on Critical Issues in C4I.

Hanlon, M. (2013). The evolution of NSK's guide robot for the visually-impaired. GizMag.com. http://www.gizmag.com/nsk-guide-robot-visually-impaired-irex/29814/

Hara, K., Azenkot, S., Campbell, M., Bennett, C. L., Le, V., Pannella, S., ... & Froehlich, J. E. (2015). Improving Public Transit Accessibility for Blind Riders by Crowdsourcing

Bus Stop Landmark Locations with Google Street View: An Extended Analysis. ACM Transactions on Accessible Computing (TACCESS), 6(2), 5.

Harper, C., Mangones, S., Hendrickson, C. T., & Samaras, C. (2015). Bounding the Potential Increases in Vehicles Miles Traveled for the Non-Driving and Elderly Populations and People with Travel-Restrictive Medical Conditions in an Automated Vehicle Environment. Proceedings of the Annual Meeting of the Transportation Research Board.

Harrell, R., Lynott, J., Guzman, S., & Lampkin, C.(2014). What is Livable? Community Preferences of Older Adults. AARP Policy Institute. http://www.aarp.org/content/dam/aarp/research/public_policy_institute/liv_com/2014/what-is-livable-report-AARP-ppi-liv-com.pdf

HERL (2015). Mobility Enhancement Robotic Wheelchair (MEBot). http://www.herl.pitt.edu/research/mebot

Hoedemaeker, M. (2013). GOAL: Growing Older, StAying mobiLe. Final Report GA No. 284924. European Commission. http://cordis.europa.eu/docs/results/284924/final1-goal-final-report.pdf

Honda (2015). ASIMO. http://world.honda.com/ASIMO/

HULOP (2015). Human-scale Localization Platform (HULOP). http://hulop.mybluemix.net

IBM (2015). IBM Traffic Prediction Tool. http://www.ibm.com/smarterplanet/us/en/transportation_systems/nextsteps/solution/N500945X17585D04.html

IDTO (2015). Integrated Dynamic Transit Operations (IDTO). http://www.its.dot.gov/dma/bundle/idto_plan.htm

Ishizuka, T. (2014). Building User Friendly Railway Information Service in Japan. Presentation at ITS World Congress.

Jamshidi, M. (2008). System of Systems Engineering: Innovations for the 21st Century. John Wiley & Sons, Inc.

Joseph, S. L., Zhang, X., Dryanovski, I., Xiao, J., Yi, C., & Tian, Y. (2013). Semantic indoor navigation with a blind-user oriented augmented reality. In Proceedings of the IEEE International Conference on Systems, Man, and Cybernetics.

Jung, S (2014). Robotic Dogs Guide the Blind: The Future of Fetching. Intel IQ. http://iq.intel.com/the-future-of-fetching-robotic-dogs-guide-the-blind/

Jungling, K., & Arens, M. (2010). Pedestrian tracking in infrared from moving vehicles. IEEE Intelligent Vehicles Symposium.

Karlsson, N., Di Bernardo, E., Ostrowski, J., Goncalves, L., Pirjanian, P., & Munich, M. E. (2005). The vSLAM algorithm for robust localization and mapping. In Proceedings of the IEEE International Conference on Robotics and Automation (ICRA). doi: 10.1109/ROBOT.2005.1570091

Kay, L. (2000). Ultrasonic eyeglasses for the blind. The Journal of the Acoustical Society of America, 108(5), 2514-2514.

Kitani, K. M., Ziebart, B., Bagnell, J. A., & Hebert, M. (2012). Activity Forecasting. European Conference on Computer Vision (ECCV). http://www.cs.cmu.edu/~kkitani/pdf/KZBH-ECCV12.pdf

Kock, B. (2015). Personal communications, VP, Enterprise Product, RideScout.

Koopman, P., & Wagner, M. (2016). Challenges in autonomous vehicle testing and validation. SAE International Journal of Transportation Safety, 4(1):15-24.

Krambeck, H. (2012). Open Data + Urban Transport = ? The World Bank. http://blogs.worldbank.org/transport/open-data-urban-transport

Kulyukin, V., Gharpure, C., Nicholson, J., & Osborne, G. (2006). Robot-assisted wayfinding for the visually impaired in structured indoor environments. Autonomous Robots, 21(1), 29-41. http://link.springer.com/article/10.1007/s10514-006-7223-8

Kulyukin, V., Gharpure, C., Nicholson, J., & Osborne, G. (2006). Robot-assisted wayfinding for the visually impaired in structured indoor environments. Autonomous Robots, 21(1), 29-41.

Lahav, O. and Mioduser, D. (2008). “Haptic feedback supporting for cognitive mapping of unknown spaces by people who are blind”, International Journal of Human-Computer Studies, vol. 66, Issue 2, pp. 23-35, 2008.

Lasecki, W., Thiha, P., Zhong, Y., Brady, E., & Bigham, J. (2013). Answering Visual Questions with Conversational Crowd Assistants. Proceedings of the International ACM SIGACCESS Conference on Computers and Accessibility (ASSETS). http://dl.acm.org/citation.cfm?id=2517033

Liao, C., Chang, J., Lee, I., & Venkatasubramanian, K. K. (2013). A Trust Model for Vehicular Network-Based Incident Reports. IEEE International Symposium on Wireless Vehicular Communications (WiVeC).

Liljas, P. (2014). Google's New Car Doesn't Have a Steering Wheel", Time.com. http://time.com/121680/google-self-driving-car-autonomous-vehicle-advanced-prototype/,

Liu, A. L., Hile, H., Borriello, G., Kautz, H., Brown, P. A., Harniss, M., & Johnson, K. (2009). Informing the design of an automated wayfinding system for individuals with cognitive impairments. In IEEE International Conference on Pervasive Computing Technologies for Healthcare.

Liu, A. L., Hile, H., Kautz, H., Borriello, G., Brown, P. A., Harniss, M., & Johnson, K. (2008). Indoor wayfinding: Developing a functional interface for individuals with cognitive impairments. Disability and Rehabilitation: Assistive Technology, 3(1-2), 69-81. http://informahealthcare.com/doi/pdfplus/10.1080/17483100701500173

Livingstone-Lee, S. A., Skelton, R. W., & Livingston, N. (2014). Transit Apps for People with Brain Injury and Other Cognitive Disabilities: The State of the Art. Assistive Technology, 26(4), 209-218. http://www.tandfonline.com/doi/abs/10.1080/10400435.2014.930076

Lo, C. (2013). Smart thinking: big data and the energy industry. Power Technology. http://www.power-technology.com/features/feature-smart-thinking-big-data-energy-industry/

Lopes, S. I., Vieira, J. M., Lopes, Ó. F., Rosa, P. R., & Dias, N. A. (2012). MobiFree: A Set of Electronic Mobility Aids for the Blind. Procedia Computer Science, 14, 10-19.

Luzeaux, D., Ruault, J.-R., Wippler, J.-L. (2011). Large scale Complex Systems and Systems of Systems Engineering: Case Studies. John Wiley & Sons, Inc.

Maier, M. W. (1999). Architecting Principles for Systems-of-Systems. Systems Engineering, 2:1, 1.

Maier, M. W., & Rechtin, E. (2013). The Art of Systems Architecting, 3rd Ed. CRC Press, Washington, DC.

Maisel, J. (2014). Factors influencing outdoor walking activity in older adults. PhD Thesis, State University of New York at Buffalo. http://pqdtopen.proquest.com/doc/1562509015.html?FMT=ABS

Mcity (2016). Mcity Test Facility. http://www.mtc.umich.edu/test-facility

Mengue-Topio, Hursula, Courbois, Yannick, Farran, Emily K., and Sockeel, Pascal, (2011). "Route learning and shortcut performance in adults with intellectual disability: A study with virtual environments," in Research in Developmental Disabilities 1(32), 345-352, doi 10.1016/j.ridd.2010.10.014, 2011.

Mertz, C., Varadharajan, S., Jose, S., Sharma, K., Wander, L., & Wang, J. (2014). City-Wide Road Distress Monitoring with Smartphones. Proceedings of ITS World Congress. http://www.ri.cmu.edu/publication_view.html?pub_id=7781

Min, B.-C., Saxena, S., Steinfeld, A., & Dias, M. B. (2015a). Incorporating information from trusted sources to enhance urban navigation for blind travelers. IEEE Conference on Robotics and Automation (ICRA).

Min, B.-C., Steinfeld, A., & Dias, M. B. (2015b). How Would You Describe Assistive Robots to People Who are Blind or Low Vision? Proceedings of the ACM/IEEE International Conference on Human-Robot Interaction: Extended Abstracts.

Mirri, S., Prandi, C., Salomoni, P. (2014). A context-aware system for personalized and accessible pedestrian paths. International Conference on High Performance Computing & Simulation (HPCS). http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6903776&isnumber=6903651

Misener, J., et al (2010). Cooperative Intersection Collision Avoidance System (CICAS): Signalized Left Turn Assist and Traffic Signal Adaptation. California PATH Research Report UCB-ITS-PRR-2010-20. University of California, Berkeley. http://www.path.berkeley.edu/sites/default/files/publications/PRR-2010-20.pdf

Mishra, S., & Lopez-Bernal, G. (2014). Enhancing Mode Choice via Crowdsourcing and Decentralization of Routing and Scheduling. Proceedings of ITS World Congress.

MIT Changing Places (2015). Mobility-On-Demand. http://cp.media.mit.edu/mobility-on-demand/

Morton, T., & Yousuf, M. (2011). Technological Innovations in Transportation for People with Disabilities Workshop Summary Report, FHWA-HRT-11-041, FHWA. http://www.fhwa.dot.gov/advancedresearch/pubs/11041/11041.pdf

Nakatsubo, K., & Yamada, K. (2010). Detecting unusual pedestrian behavior toward own vehicle for vehicle-to-pedestrian collision avoidance. IEEE Intelligent Vehicles Symposium 2010.

Nassir, N., Hickman, M., Ma, Z.-L. (2015). Activity detection and transfer identification for public transit fare card data. Transportation, 42(4), 683-705. http://link.springer.com/article/10.1007/s11116-015-9601-6

6 References

NavCog (2015). Cognitive Assistance Lab. http://www.cs.cmu.edu/~NavCog/

Newman, J. (2015). Uber CEO Would Replace Drivers with Self-Driving Cars, Time.com. http://time.com/132124/uber-self-driving-cars/

Northrop, L., Feiler, P., Gabriel, R. P., Goodenough, J., Linger, R., Longstaff, T., Kazman, R. Klein, M. H., Northrop, L. M., & Schmidt, D. (2006). Ultra-Large-Scale Systems: The Software Challenge of the Future. Software Engineering Institute, Carnegie Mellon University. http://resources.sei.cmu.edu/library/asset-view.cfm?assetID=30519

O'Brien, E. E., Mohtar, A. A., Diment, L. E., & Reynolds, K. J. (2014). A detachable electronic device for use with a long white cane to assist with mobility. Assistive Technology, 26(4), 219-226.

O'Connor, M. C. (2015). ARIBO: Bringing Autonomous Vehicles to Military Bases, Campuses and Even City Streets. IOT Journal. http://www.iotjournal.com/articles/view?12607

Pai, D., Malpani, M., Sasi, I., Aggarwal, N., & Mantripragada, P. S. (2012, June). Padati: A robust pedestrian dead reckoning system on smartphones. In IEEE International Conference on Trust, Security and Privacy in Computing and Communications (TrustCom). doi= 10.1109/TrustCom.2012.218

Palfinger (2015). Passenger Lifts. https://www.palfinger.com/en/mde/products/passenger-lifts/models

Parada-Loira, F., & Alba-Castro, J. L. (2010). Local Contour Patterns for fast traffic sign detection. IEEE Intelligent Vehicles Symposium.

Personal Robotics Lab (2015). Personal Robotics Lab. https://personalrobotics.ri.cmu.edu

Petutschnig, B., Rüger, B., Tauschitz, P, Simic, G. (2012). PubTrans4All: Final Report on Project Results. http://www.pubtrans4all.eu/images/doks/PT4A_D5.4_FinalReportonProjectResults_20121130.pdf

PMAR PICAV (2015). PICAV. http://www.dimec.unige.it/pmar/picav/

Porter, J., Cheung, K., Giampapa, J. A., & Dolan, J. M. (2013). A Reliability Analysis Technique for Estimating Sequentially Coordinated Multirobot Mission Performance. Proceedings of the International Conference on Principles and Practice of Multi-Agent

Systems (PRIMA), pp. 276-291. Springer Verlag Lecture Notes in Computer Science. http://www.ri.cmu.edu/publication_view.html?pub_id=7618

Pratama, A. R., & Hidayat, R. (2012). Smartphone-based pedestrian dead reckoning as an indoor positioning system. In IEEE International Conference on System Engineering and Technology (ICSET).

Project Tango (2015). Project Tango. http://www.google.com/atap/projecttango

PubTrans4All (2015). PubTrans4All. http://www.pubtrans4all.eu/en/

Quadrifoglio, L. (2013). Innovative Operating Strategies for Paratransit Services. Final Report for Transit IDEA Project 73. Transportation Research Board. http://onlinepubs.trb.org/Onlinepubs/IDEA/FinalReports/Transit/Transit73.pdf

Ramteke, D., Kansal, G., & Madhab, B. (2014). Accessible Engineering Drawings for Visually Impaired Machine Operators. Assistive Technology, 26(4), 196-201.

Ran, L., Helal, S., & Moore, S. (2004). Drishti: an integrated indoor/outdoor blind navigation system and service. Proceedings of the IEEE Conference on Pervasive Computing and Communications. http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=1276842

Ravi, N., Shankar, P., Frankel, A., Elgammal, A., & Iftode, L. (2006). Indoor localization using camera phones. In IEEE Workshop on Mobile Computing Systems and Applications. http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=1691710

REVAMP (2015). Real-Time Scheduling of ACCESS Paratransit Transportation. http://www.ri.cmu.edu/research_project_detail.html?type=description&project_id=754&menu_id=261

Robot Interaction for Visually Impaired Adults. Proceedings of the IEEE International Conference on Robotics and Automation (ICRA).

Robotics & Mechanisms Laboratory (2015). Blind Driver Challenge. http://www.romela.org/main/Blind_Driver_Challenge

Ross, J. N. (2013). Check out Ford's fully automated self-parking car [w/video]. Autoblog. http://www.autoblog.com/2013/10/09/ford-fully-automated-self-parking-car-video/

Sánchez, J., & de Borba Campos, M. (2013). Audio transportation system for blind people. In Universal Access in Human-Computer Interaction. Applications and Services for Quality of Life (pp. 661-670). Springer Berlin Heidelberg.

Sánchez, J., & Sáenz, M. (2010). Metro navigation for the blind. Computers & Education, 55(3), 970-981.

Sanchez, J., et al (2010). “Navigation for the Blind through Audio-Based Virtual Environments” CHI ’10 Extended Abstracts on Human Factors in Computing Systems New York, 3409-3414, 2010.

SARTRE (2015). SARTRE. http://www.sartre-project.eu/en/Sidor/default.aspx

Scalevo (2015. Scalevo. http://scalevo.ch

Sharifi, M. S., Stuart, D., Christensen, K., & Chen, A. (2015). Exploring Traffic Flow Characteristics and Walking Speeds of Heterogeneous Pedestrian Stream Involving Individuals with Disabilities in Different Walking Environments. Transportation Research Board 94th Annual Meeting. http://trid.trb.org/view.aspx?id=1337264

Shino, M., Tomokuni, N., Murata, G., & Segawa, M. (2014). Wheeled inverted pendulum type robotic wheelchair with integrated control of seat slider and rotary link between wheels for climbing stairs. IEEE Workshop on Advanced Robotics and its Social Impacts (ARSO). http://ieeexplore.ieee.org/xpl/login.jsp?tp=&arnumber=7020991

Simpson, R. C., Poirot, D., & Baxter, F. (2002). The Hephaestus smart wheelchair system, IEEE Transactions on Neural Systems and Rehabilitation Engineering, 10(2):118-122.

Steinfeld, A. (2008). Smart Systems in Personal Transportation. In A. Helal, M. Mokhtari, & B. Abdulrazak (Eds.), The Engineering Handbook on Smart Technology for Aging, Disability and Independence, John Wiley & Sons. ISBN 0471711551, Computer Engineering Series.

Steinfeld, A. (2010). Universal design of automobiles. In W. F. E. Preiser & K. H. Smith (Eds.), Universal Design Handbook, 2nd Edition. New York, NY: McGraw-Hill.

Steinfeld, A., Rao, S. L., Tran, A., Zimmerman, J., & Tomasic, A. (2012). Co-producing value through public transit information services. International Conference on Human Side of Service Engineering. (Co-Located with the International Conference on Applied Human Factors and Ergonomics)

Steinfeld, A., Zimmerman, J., & Tomasic, A. (2014). Bringing Customers Back into Transportation: Citizen-Driven Transit Service Innovation via Social Computing. In S. Bregman, K. E. Watkins (Eds.), Best Practices for Transportation Agency Use of Social Media. Boca Raton, FL: CRC Press.

Steinfeld, E., Paquet, V., Lenker, J., D'Souza, C., & Maisel, J. (2010). Universal Design Research on Boarding and Using Buses. Proceedings of the 12th International Conference on Mobility and Transport for Elderly and Disabled Persons (TRANSED 2010), Hong Kong, June 2-4, 2010.

Stoklosa, A. (2013). We Watch an Audi A7 Drive Away and Park in a Garage All By Itself—With No Driver [2013 CES]. Car and Driver. http://blog.caranddriver.com/audi-demonstrates-driverless-self-parking-a7-in-vegas-parking-garage/

Sullivan, K. (2007). Edge Programming. Proceedings of the International Conference on Software Engineering Workshops.

Suppé, A., Navarro-Serment, L. & Steinfeld, A. (2010). Semi-autonomous virtual valet parking. Proceedings of the Second International Conference on Automotive User Interfaces and Interactive Vehicular Applications (AutomotiveUI). http://www.auto-ui.org/10/proceedings/p139.pdf

Sycara, K., Glinton, R., Yu, B., Giampapa, J., Owens, S., Lewis, M., & Grindle, L. C. (2009). An integrated approach to high-level information fusion. Information Fusion, 10(1), 25-50.

Sycara, K., Paolucci, M., Ankolekar, A., & Srinivasan, N. (2011). Automated discovery, interaction and composition of semantic web services. Web Semantics: Science, Services and Agents on the World Wide Web, 1(1).

Tan, H.-S., & Huang, J. (2014). Design of a High-Performance Automatic Steering Controller for Bus Revenue Service Based on How Drivers Steer. IEEE Transactions on Robotics, 30(5), 1137-1147. http://dx.doi.org/10.1109/TRO.2014.2331092

Tan, H.-S., Bu, F., Johnston, S., Bougler, B., Zhang, W.-B., & Sun, S. (2009). Field Demonstration and Tests of Lane Assist/Guidance and Precision Docking Technology. PATH Research Report UCB-ITS-PRR-2009-12. University of California, Berkeley.

TechBridgeWorld (2015). NavPal. http://www.cs.cmu.edu/~navpal/

Tesla (2016). Summon Your Tesla from Your Phone. https://www.teslamotors.com/blog/summon-your-tesla-your-phone

Tian, Z., Zhang, Y., Zhou, M., & Liu, Y. (2014). Pedestrian dead reckoning for MARG navigation using a smartphone. EURASIP Journal on Advances in Signal Processing, 2014(1), 1-9. http://dx.doi.org/10.1186/1687-6180-2014-65.

Timcho, T. (2014). Integrated Dynamic Transit Operations (IDTO) Prototype Development and Demonstration. T3 Webinar on Transit Safety & Mobility Applications in a Connected Vehicle World. http://www.pcb.its.dot.gov/t3/s140514/s140514_cv_transit_apps_presentation_timcho.pdf

Tomasic, A., Steinfeld, A., Zimmerman, J., & Huang, Y. (2014). Motivating contribution in a participatory sensing system via quid-pro-quo. In Proceedings of the ACM Conference on Computer Supported Cooperative Work and Social Computing (CSCW).

Tomasic, A., Zimmerman, J., Garrod, C., Huang, Y., Nip, T., & Steinfeld, A. (2015). The performance of a crowdsourced transportation information system. Transportation Research Board 2015 Annual Meeting. Washington, DC: Transportation Research Board.

Tomokuni, N., & Shino, M. (2012). Wheeled inverted-pendulum-type personal mobility robot with collaborative control of seat slider and leg wheels. IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS). http://ieeexplore.ieee.org/xpl/login.jsp?tp=&arnumber=6385572

Toyota (2004). i-unit Overview. http://www.toyota.co.jp/en/news/04/1203_1e.html

Toyota (2015). Partner Robot. http://www.toyota-global.com/innovation/partner_robot/

Transportation.gov (2015). Small Business Innovation Research program makes crossing the street safer. https://www.transportation.gov/fastlane/sbir-program-makes-crossing-street-safer

TRIP (2015). CHAUFFEUR II. http://www.transport-research.info/web/projects/project_details.cfm?id=15277

UBER & MADD (2015). More options. Shifting mindsets. Driving better choices. http://newsroom.uber.com/2015/01/making-our-roads-safer-for-everyone-2/

Ulrich, I., & Borenstein, J. (2001). The GuideCane-applying mobile robot technologies to assist the visually impaired. IEEE Transactions on Systems, Man and Cybernetics, Part A: Systems and Humans, 31(2), 131-136.

Urmson, C., Baker, C., Dolan, J., Rybski, P., Salesky, B., Whittaker, W., Ferguson, D., & Darms, M. (2009). Autonomous Driving in Traffic: Boss and the Urban Challenge. AI Magazine, 30(2), 17-28. http://www.aaai.org/ojs/index.php/aimagazine/article/view/2238

Valeo Park4U Remote (2015). Valeo Park4U Remote. http://www.valeoservice.com/html/egypt/en/products.focusdetail-valet_park4u%C2%AE,_the_automated_parking_system-678248713529DA1BBB3A7C.html

Vales-Alonso, J., Egea-Lopez, E., Muoz-Gea, J. P., Garcia-Haro, J., Belzunce-Arcos, F., Esparza-Garcia, M. A., Perez-Maogil, J. M., Martinez-Alvarez, R., Gil-Castieira, F., & Gonzalez-Castao, F. J. (2008). UCare: Context-Aware Services for Disabled Users in Urban Environments. International Conference on Mobile Ubiquitous Computing, Systems, Services and Technologies (UBICOMM). http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=4641336&isnumber=4641296

van Amelsfort, D., Hjalmarsson, A., & Karlsson, M. (2014). Changing Travel Behavior Through Incentives Using a Smartphone Application with Automatic Travel Behavior Detection: Results from Gothenburg. Proceedings of ITS World Congress.

VizWiz (2015). VizWiz. http://www.vizwiz.org

W3C (2001). Web Ontology Language (OWL). http://www.w3.org/2001/sw/wiki/OWL

Wayfindr.net (2015). Wayfindr. http://www.wayfindr.net

Wallich, P. (2012). The DIY Kid-tracking Drone. IEEE Spectrum. http://spectrum.ieee.org/geek-life/hands-on/the-diy-kidtracking-drone

Wang, H., Tsai, C.-Y., Jeannis, H., Chung, C.-S., Kelleher, A., Grindle, G. G., & Cooper, R. A. (2014). Stability analysis of electrical powered wheelchair-mounted robotic-assisted transfer device. Journal of Rehabilitation Research & Development (JRRD), 51(5), 761-774. http://www.rehab.research.va.gov/JOUR/2014/515/jrrd-2013-11-0240.html

Werner, C. A. (2011). The Older Population: 2010. 2010 Census Briefs. U.S. Census Bureau. https://www.census.gov/prod/cen2010/briefs/c2010br-09.pdf

Wikipedia (2015). Hiriko. https://en.wikipedia.org/wiki/Hiriko

Wollaston, V. (2015). `Robots on reins' could soon replace guide dogs: Machines use tactile sensor and vibrations to help people navigate. Tthe Daily Mail Online. http://www.dailymail.co.uk/sciencetech/article-3011069/Robots-reins-replace-guide-dogs-Machines-use-tactile-sensors-vibrations-help-people-navigate.html

Wu, X., Miucic, R., Yang, S., Al-Stouhi, S., Misener, J., Bai, S., Chan, W.-C. (2014). Cars Talk to Phones: A DSRC Based Vehicle-Pedestrian Safety System. IEEE Vehicular Technology Conference (VTC Fall). http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6965898&isnumber=6965690

6 References

Xiao, J., Joseph, S. L., Zhang, X., Li, B., Li, X., & Zhang, J. (2015). An assistive navigation framework for the visually impaired, IEEE Transactions on Human-Machine Systems, 45(5): 635-640.

Xiong, X., Oliver, A. A., Akinci, B., & Huber, D. (2013). Automatic creation of semantically rich 3D building models from laser scanner data. Automation in Construction, 31:325-337.

Ziebart, B. D., Maas, A., Dey, A. K., & Bagnell, J. A. (2008). Navigate Like a Cabbie: Probabilistic Reasoning from Observed Context-Aware Behavior. International Conference on Ubiquitous Computing (Ubicomp). http://www.cs.uic.edu/pub/Ziebart/Publications/navigate-bziebart.pdf