Working Paper #1

Automated Vehicle Technology
Deployment Scenarios for Public Transit

To the

National Highway Cooperative Research Program (NCHRP)

On project

20-102 (02): Impacts of Laws and Regulations on Automation Technology for Transit

June 2016

Revised March 2017

From

Kimley-Horn – Douglas Gettman, Ph.D.

Texas Southern University – J. Sam Lott, Principal Investigator

Cambridge Systematics – Tom Harrington, AICP

Table of Contents

List of Appendices

Table of Figures

Table of Tables

March 2017 Revisions

The following changes have been made to the June 2016 version of this Working Paper #1. This superseding version also has had other minor editorial changes made throughout the document that do not affect meaning.

1. **Forward** – A wholly new insertion of a Forward which will be included in all subsequent Working Papers.
2. **Chapter 1** – Revisions to update the references to NHTSA and SAE levels of driving automation.
3. **Chapter 3** – Revisions to update the references to NHTSA and SAE levels of driving automation, and to replace the related automation figure with a new table.
4. **Chapter 4** – Revisions to reference "NHTSA/SAE" levels of driving automation and revisions to move a discussion of liability and risk for passengers to a new research project recommendation.
5. **Chapter 7** – Addition of recommended research projects list.
6. **Glossary of Terms** – Updated to include newly added SAE J3016 terms and acronyms and other missing terms.
7. **Appendix A** – Corrections to the text.
8. **Appendix B** – Added to provide a summary interpretation of SAE J3016 standard definitions and taxonomy as they relate to AV public transit systems.

Foreword

This working paper uses the following terminology and focus of its content in a manner consistent with all the associated working papers of the NCHRP 20-102(02) project.

Definition of Automated Vehicle (AV) Transit – The “system” comprising AV Transit includes:

1. Driving automation system(s) and technology per SAE J3016[1]
    a. Other vehicle systems and components which provide driver assistance such as lane departure warning when a human driver is performing the dynamic driving task (DDT) from inside the vehicle or from a remote location; and
2. Other monitoring, supervisory control and passenger safety systems, technologies and facilities necessary for public transit service, such as precision docking, automated door operation, and dispatch functions.

Definition of Transit Vehicle Operator – The typical term used to identify the person operating a transit vehicle is the “vehicle operator”. However, under SAE J3016 definitions and terminology, a human “driver” is the person who manually exercises in-vehicle braking, accelerating, steering, and transmission gear selection input devices to operate a vehicle. Considering the SAE standard’s intent to define terms for driving automation systems only, the term vehicle driver is specified. In the working papers, the terms vehicle driver and vehicle operator may be used interchangeably, depending on the context and point of emphasis. Likewise, the terms “remote driver” (per SAE J3016) and “remote operator” will likewise be used interchangeably.

Definition of Transit Operating Agency – Transit operating agencies can be any type of public, governmental or non-profit entity, such as transit authorities created with certain governmental responsibilities; municipal, county and state government public transportation departments; medical/educational institutions; and local management authorities/districts.

Focused Nature of the Working Papers – Each working paper has a focused purpose and is not intended to provide a comprehensive set of steps, actions or preparations encompassing the full evolution of AV Transit technology applications in public transit service. Some aspects of this project’s research have focused more on the ultimate operating conditions when AV technology is fully mature to understand the long term, ultimate state of automated transit technology, policy and regulations.

Conclusions on AV Transit in the Final Report – The Final Report will address information on the probable benefits and impacts of AV Transit, as well as articulate a roadmap of further research activities that technology, policy and regulations should follow over the next few decades.

[1] SAE J3016 is the Society of Automotive Engineers Standard titled – Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles; revised September 30, 2016.

1. Introduction to Automated Vehicle Technology

This series of working papers is being conducted under the auspices of the National Academy of Sciences/Transportation Research Board as a work assignment through the National Cooperative Highway Research Program (NCHRP). The assignment concerns studies of advanced vehicle technologies and their implications for public transit.

Major advances in robotics, artificial intelligence, sensors, and processing technology are driving the automotive industry toward the eventual goal of fully automated vehicles (AVs) operating along all types of roadway systems. These advances offer significant opportunities to improve transit services by reducing cost, extending reach, and improving safety of transit vehicles operating on the general roadway network.

Significant changes are occurring every month in the field of driving automation systems while automated and connected vehicle technologies are in a process of intense research and development. Since this Working Paper #1 was first released in June of 2016, several new vehicle technologies have been announced, major original equipment manufacturers (OEMs) in the automotive field have announced their target date for mass producing highly automated vehicles for private and public transit use, the National Highway Traffic Safety Administration (NHTSA) has released a major new policy statement, and the Society of Automotive Engineers (SAE) has released a major update to its SAE J3016 standard that defines the automotive industry's consensus of terms and taxonomy of driving automation systems for on-roadway motor vehicles.

Purpose and Organization of the NCHRP 20-102(02) Study

This project identifies a roadmap of activities to be performed by industry groups, legislatures, the federal government, and others that will facilitate automated roadway transit operations. The project is focused on the potential barriers imposed by operating authority policies, agency regulations, and governmental laws relative to the transit environment. Without adjustment, the combination of new technology with

The levels of automation referenced herein are taken from the NHTSA policy document released in September 2016, as given below. These are in turn based on definitions by Society of Automotive Engineers (SAE).

- **Level 0** – the human driver does everything.
- **Level 1** – an automated system on the vehicle can *sometimes assist* the human driver conduct *some parts of* the driving task.
- **Level 2** – an automated system on the vehicle can conduct some parts of the driving task, while the human continues to monitor the driving environment and performs the rest of the driving task.
- **Level 3** – an automated system can both conduct some parts of the driving task and monitor the driving environment *in some instances*, but the human driver must be ready to take back control when the automated system requests.
- **Level 4** – an automated system can conduct the driving task and monitor the driving environment, and the human need not take back control, but the automated system can operate only in certain environments and under certain conditions.
- **Level 5** – the automated system can perform all driving tasks, under all conditions that a human driver could perform them.

NOTE: These levels of driving automation will be referred to in this document as **L1**, **L2**, **L3**, **L4** and **L5**. Refer to Chapter 3 and **Appendix B** for a more complete discussion.

old rules could result in undue delays and restrictions to deployment, which reduces the cumulative societal benefits that could have accrued if automated systems technology was implemented earlier.

The project consists of five tasks:

1. Develop a technology baseline for the current state of the practice in AV transit
2. Identify issues and impacts on transit vehicle driver and associated staff
3. Identify government regulations and laws impacting AV adoption in transit
4. Develop an implementation plan to address the challenges identified in Tasks 1-3
5. Prepare a final report consolidating Tasks 1-4

We have organized the five tasks to produce six working papers, and an implementation roadmap for transit automation in the final report. The Working Paper #1 provides an overview of the deployment scenarios for AV technology in transit applications.

Working paper #2 provides a foundation of technical information concerning safety from which subsequent considerations of operating agency policy and governmental safety regulations can be addressed.

Working Papers #3 Workforce Deployment and #4 Operating Agency Policy address the implications of automating roadway transit vehicles with respect to local operating agency issues, including labor relations and training, broad operating planning and policy, and response to governmental laws and regulations.

Working Paper #5 addresses issues and possible changes to the federal and state governmental laws and regulations over public transit that should be researched, as well as issues and possible changes that may be required in vehicle designs to effectively comply with regulations. Finally, Working Paper #6 addresses the preliminary timeline for deployment of progressive transit automation in overall consideration of technology, policy and regulatory changes that will be required.

Then in the final report for the project, an assessment is discussed of the overall benefits and impacts of AV technology on public transit, and a proposed "roadmap" for further research will be described.

State of AV Technology Development

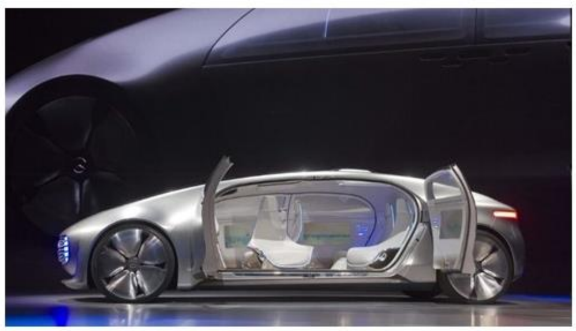
Advances in research and development of AV technology are being announced almost daily, and industry perception is continually changing for even the most knowledgeable people in the field. Therefore, the information here on the state of AV technology is provided in this paper as of June 2016 and cannot be considered to be comprehensive. New announcements or developments could substantially change these contents as time progresses, particularly regarding the technology availability timeline. Even so, the description of AV public transit applications within a single report is important as a benchmark.

There are parallel research and development processes occurring between AV, which hold the promise of driverless operations, and connected vehicle (CV) communication technologies that enable safer and more efficient driving for both human- and computer-driven vehicles through warnings and detailed information sharing.

Automated Vehicles – More than 20 years ago, AV technology advanced in the U.S. via the USDOT Intelligent Vehicle Highway System (IVHS) Automated Highway System (AHS) program (although many research initiatives preceded this technology demonstration dating back to the 1950s)[2]. In the early 2000s, development was reinvigorated by the DARPA Grand and Urban Challenges, which brought universities and private sector teams together[3]. AV technology today is generally advancing under private sector initiatives of the automobile industry original equipment manufacturers (OEMS), Tier 1 suppliers, software companies such as Google, robotics-oriented start-up companies, and combinations thereof.

Major recent strides in accuracy, affordability, and capability of sensors, software, computing, and geo-location technology are enabling AVs. A few OEMs are actively developing marketable automated vehicle models for the industry shown in **Figure 1**, and almost all major automobile manufacturers are racing to bring these new product offers to the market place as soon as possible.

Figure 1. Automated Roadway Vehicles Will Be on the Market by 2020s



Source: Mercedes

Source: Audi

Source: Nissan

[2] http://onlinepubs.trb.org/onlinepubs/sr/sr253.html

[3] https://en.wikipedia.org/wiki/DARPA_Grand_Challenge

Connected Vehicles – Over the last 20+ years, CV technology was primarily driven by USDOT initiatives. Some of the CV program evolution was in direct response to the numerous challenges of AHS' grand vision. CV technologies use wireless communications between vehicles, the infrastructure, and mobile devices to improve safety and mobility and reduce environmental impacts of human-operated vehicles[4]. NHTSA released an advance notice of proposed rulemaking in August 2014 requiring DSRC 5.9 GHz communications capability as a standard for light vehicle manufacturers and is expected to do the same for heavy-duty trucks and buses within the next year[5]. As of 2016, these mandates have not been made, but are still considered imminent.

CV communications can also use 3G and Fourth-Generation Long-Term Evolution (4G/5G LTE) technology for non-safety-critical applications. Vehicle-to-vehicle (V2V) and vehicle-to-other road users (V2X) technologies can improve safety by warning bus drivers of obstacles and imminent crash threats. Vehicle-to-infrastructure (V2I) applications can improve both transit vehicle travel efficiency and passenger service. CV technologies have been used for over 20 years now in hundreds of locales around the U.S. and the world for providing priority green time at traffic signals, known as transit signal priority (TSP).

Effectively implementing connectivity through V2V and V2I communications requires USDOT, state DOTs, and local agency coordination, communication standards, OEM cooperation, and potentially international governmental coordination within the global automobile, transit, and commercial vehicle markets. Technology readiness was demonstrated in Ann Arbor, MI by UMRTI in the USDOT Safety Pilot program[6]. Large-scale field tests of CV applications in the U.S. are scheduled for 2018 in Tampa, FL; New York, NY; and the State of Wyoming, some of which include transit applications. These efforts are all on-going and will not be addressed in this document[7].

Automated Transit Vehicles – The prospects for AV transit applications in general mixed-traffic operation now appears realistic in the foreseeable future. Automated steering, throttle/propulsion and braking, and precision docking controls for buses have already been demonstrated to improve safety and efficiencies of buses augmenting the skills of human drivers[8]. Automated transit systems on fixed-guideway facilities have been in use for over 40 years[9]. These transit systems have sophisticated supervisory control functions (connected technologies) necessary for safe and efficient management of even just a single transit line with a small number of individual vehicles. We foresee the marriage of the CV and AV worlds to enable truly driverless transit vehicles in the long-term, with corresponding enabling developments in transit station and fixed facility design. In addition, we believe AV transit

[4] http://www.its.dot.gov/landing/cv.htm

[5] http://www.nhtsa.gov/Research/Crash+Avoidance/Vehicle-to-Vehicle+Communications+for+Safety

[6] http://www.its.dot.gov/safety_pilot/

[7] http://www.its.dot.gov/pilots/

[8] http://www.path.berkeley.edu/sites/default/files/documents/IM_15-1_low%20%282%29.pdf

[9] https://en.wikipedia.org/wiki/Automated_guideway_transit

applications will provide operational flexibility resulting in a whole paradigm shift that must now begin to be included in planning studies as shown in **Figure 2**.

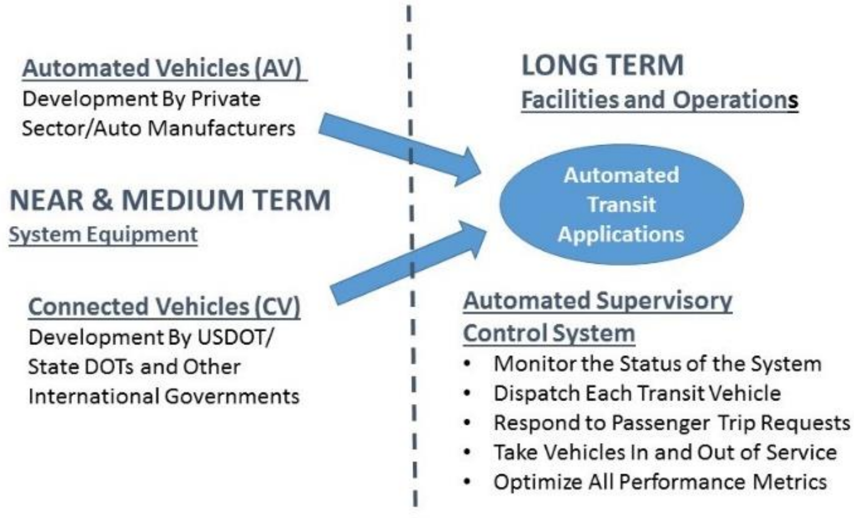


Figure 2. Parallel AV/CV Development Paths Potentially Coming Together for AV Transit Operations

Definitions of Business Models and Service Types

Much discussion is underway in the transportation industry about the place for the “private business model” of automated car services (e.g., automated Uber or Lyft), and the differences of services through a “public transit business model.” Current terminology being used to address this private business model is a transportation network company (TNC), and some have referred to this as a “private transit” service. There are several hybrid combinations of these basic business models. A public transit entity could contract with a private vehicle operator for services and establish a formal public/private partnership(s) where the public entity provides a franchise to a private operator to use public assets (i.e. land/right-of-way) in providing the transit service. Business models will be addressed in subsequent working papers as they relate to policy, regulations, and laws.

The relevant topic of discussion in this working paper, however, is the type of public transit service that is provided by AV technology. For example, although fixed-route public transit service will certainly continue into perpetuity along very high demand corridors as the basic backbone of public transit service, a new type of “first mile/last mile” service will likely develop, which is being described by Federal Transit Administration (FTA) as a “mobility on-demand” type of transit[10]. A potential timeline from AV pilots, fixed-route services, first-mile/last-mile services, and then to circulation functions within urban districts and subregional areas is introduced in Chapter 4 and summarized in Chapter 6.

The following provides the basic assumptions defining these different service types for purposes of this working paper, with an acknowledgement that these definitions could change

[10] https://www.transit.dot.gov/funding/applying/notices-funding/mobility-demand-mod-sandbox-program

as industry representatives become involved in vetting the progressive conclusions and recommendations of this study in subsequent tasks.

AV Fixed-Route Transit Service – Common transit service within urban areas providing traditional customer service with a fixed set of origin/destinations visited by the transit vehicle regardless of demand, but without a human driver. This fixed route service would operate on set schedules/headways and vehicles on some routes could potentially only make stops when passengers indicate their intent to board or alight the vehicle.

AV On-Demand Transit Service – Common transit service within urban areas that provides automated dispatching and management of transit vehicles for a user-selected origin/destination combination. Rides are shared among any member of the public. Although solo rides are possible if the demand is very low for a given origin/destination pair and for a given time of day, this will not be guaranteed. The service operates much like a *horizontal elevator*. New passengers may enter or exit at any point on a route. This public transit service would have specified pick-up/drop-off locations designed for passenger convenience, which may number many more locations than existing fixed-route transit service. This service may provide specialized (i.e. minimized delay) routing of a given vehicle through the network of routes given the origins and destinations of the riders.

AV Paratransit or Rural On-Demand Transit Service – Working from the concept of paratransit as it is provided today, each registered user will be able to pre-define their personal pick-up and drop-off locations and time of day they will be taking their trip. Trip details are customizable to that specific users personal needs, and changes are possible in real time as necessary. Advance reservations will be required only shortly (i.e. an intentionally vague time frame that could range from minutes to hours) before the trip actually occurs (depending on vehicle availability and trip location). When the trip reservation includes service involving a disability that requires special attention with human oversight of the boarding and alighting process (e.g., conditions where special equipment or visual/audio attention is required to assist the passenger), this may be accomplished via remote viewing/control of the vehicle and its special equipment by transit system personnel located in the operations control center or an on-board "customer service agent."

AV "Automated Taxi" On-Demand Service – An on-demand vehicle service provides customized rides which may or may not include ride sharing (as determined by pricing and user preferences). Passenger pick-up and drop-off would be determined by the user – e.g., my home driveway, my airline terminal curbfront by "door #3," my specific destination street address at the curb, and so on. These vehicle services operate like taxi services operate today.

References throughout this project's documentation to these basic service types using fully automated vehicles will apply the descriptor of "AV" for automated transit vehicles which may be both autonomous and connected vehicles. The technical features of controls and sensors, communications connectivity, and artificial intelligence that comprise the functional capabilities of "automated vehicles" are discussed in Chapter 3.

2. Historical Context of Automated Transit Systems

Automated Transit Systems on *fixed guideways* have been in operation for more than 40 years. In this chapter, we detail some of this history and motivate future discussion of the regulatory challenges facing the operation of AV transit services *without* dedicated guideways.

Automated Transit Systems: 1964 – 2016

Automated Guideway Transit/Automated People Mover Systems – The USDOT federally funded pilot project of the first fully automated guideway transit system began passenger service in 1964 at Pittsburgh's South Park (see **Figure 3**). Following this prototype system's demonstration of automation viability came the airport systems at Tampa Airport and Seattle/Tacoma Airports. These initial systems became known as automated guideway transit (AGT) systems, but the more whimsical automated people mover (APM) moniker soon became commonly used. Throughout the 1970s and 1980 the successful deployment of fully automated train systems began to allow fundamentally different configurations of airport terminal facilities to be created, such as the massive Atlanta airport with its spine APM system connecting numerous airside concourses. The Atlanta system has now been expanded to carry secure air passengers between destinations spread over more than a mile across the airfield. Many more airport APM systems have been built by numerous system suppliers in the following years.

A USDOT federally funded demonstration of the first ***urban*** APM application was the initial "loop" system in downtown Miami that began service in the mid-1980s. This "Metromover" was extended in the 1990s to connect several adjacent business districts with the Central Business District (CBD) and provide access points at over 20 station locations. Other urban systems were soon in service throughout the world, beginning with the fully automated urban system in Lille, France, which began service in 1983 and was followed by systems throughout Europe and Asia. One of the first **regional-scale** automated systems was the Vancouver Sky Train, which began fully automated passenger service in the mid-1980s and expanded several times to include multiple lines. Many fully automated **metro** systems are now in service throughout the world, such as the Singapore Metro subway system runs without an operator or even attendant transit personnel onboard[11]. In general, the term APM is commonly applied to **airport and special-use systems**, and the term AGT is commonly applied to **larger urban systems that reach a full regional/metropolitan scale** of service.

The last 50 years of AGT/APM system development has also provided a strong platform from which AV transit applications can extend. Fully automated, driverless trains have been safely operated over many millions of vehicle-miles with no service-related passenger fatalities. This is a testament to the rigorous and highly standardized testing process and safety regulations and procedures for AGT/APM systems (ASCE 21-13; IEC 62267)[12]. The AGT/APM industry

[11] Observatory of Automated Metros, http://metroautomation.org/.

[12] http://orfe.princeton.edu/~alaink/SmartDrivingCars/Stanford_TRB_Conf_July2013/Transit&SharedMobility/Lott_TRB_Stanford.pdf

prepared this important foundation upon which the future mass transit applications of AV driverless roadway technology can build.

The functional elements of conventional **automated train control systems** will be important reference points as new robotic vehicles are deployed in transit service. These aspects of transit operations are defined below from the ASCE 21-13 APM Standard and the relevant functionality will be addressed further in subsequent chapters of this working paper.

- **Automatic Train Control (ATC)** – The system for automatically controlling train movement, enforcing train safety, and directing train operations. ATC includes subsystems for automatic train operation (ATO), automatic train protection (ATP) and automatic train supervision (ATS).
- **Automatic Train Operation (ATO)** – That subsystem within the ATC system which performs any or all of the functions of speed regulation, programmed stopping, door and dwell time control, and other functions otherwise assigned to the train operator.
- **Automatic Train Protection (ATP)** – That subsystem within the ATC system which provides the primary protection for passengers, personnel, and equipment against the hazards of operations[13] conducted under automatic control.
- **Automatic Train Supervision (ATS)** – That subsystem within the ATC system which monitors and manages the overall operation of the APM system and provides the interface between the system and the central control operator.

[13] Safety analyses of AGT/APM systems identify hazards which describe a condition that could result in an accident, without identifying an accident or potential causes. Distinguishing the hazard from the accident and its causes facilitates hazard analysis and selection of the mitigations designed to eliminate or reduce risk. Examples of hazards are train-to-train collision, train-to-structure collision, train collision with other object, and person struck by a train.

South Park Demonstration Project – Pittsburgh began service in 1964
Source: Official Skybus Webpage, http://www.brooklineconnection.com/history/Facts/Skybus.html

Miami Metromover began service in 1986; Source: Kimley-Horn

Singapore Land Transport Authority Northeast Line began passenger service in 2003, followed by the Circle Line (2011) and Downtown Line (2013) (Source: Kimley-Horn)

Figure 3. 50-Year History of Fully Automated Guideway Transit Systems

Robotic Vehicles in Automated Transit Network Systems – At the time APM/AGT technology began to develop in the 1960s and 1970s, an extension of that concept began to develop for automated guideway systems that would provide a “network” configuration of guideways and stations along which small individual vehicles would operate. The concept included off-line stations such that AVs could bypass on the main line. This birthed the concept of providing “personalized” service directly between a passenger’s origin station to their destination station without stopping at any other stations along the route. Originally known as **personal rapid transit** (PRT) and **group rapid transit** (GRT), the concept was aggressively pursued through major planning projects and system technology development beginning in the 1970s. One of the first Urban Mass Transit Administration (UMTA) people mover system demonstration projects was the West Virginia University APM system in Morgantown, West Virginia. This system is currently being rehabilitated and remains the only network guideway system in the U.S. with trains dispatched by trip requests of passenger in the stations – a demand-response dispatching concept integral to the PRT/GRT concept[14].

Over the past 25 years there have been several examples of PRT/GRT systems in small, specialized public transit systems, which deployed robotic vehicles operating along dedicated transitways. These prototype systems (i.e., one of a kind systems) have been operating completely unmanned and steering themselves without physical guidance mechanisms. For purposes of this discussion, each are treated as “guideway” systems in that the vehicles follow a fixed route within a prescribed “transitway” similar to systems that are physically guided along their path. These robotic systems generally fall into the class of AGT called PRT, GRT, or in more common terminology used in recent years – “automated transit network” (ATN).

Three such systems are currently in public transit service using robotic vehicles steering themselves along a fixed route transitway without physical guidance, although all **either calibrate their position from magnetic markers along the guideway** or **sense the guideway sidewalls using laser technology**. Two different size robotic vehicle systems built by a system supplier from the Netherlands are shown in their deployment locations in **Figure 4.** The larger vehicles in the figure have been operating in a business district since 2005, and the smaller vehicles have been carrying passengers within the office complex since 2010. The other operating system is located at Heathrow airport in London England and began passenger service in 2011. Further information and photographs of this special class of automated people mover system can be found in **Appendix A**.

[14] https://en.wikipedia.org/wiki/Automated_guideway_transit

Figure 4. Robotic Vehicle ATN Systems Currently Operating in the Netherlands (photos above) and in Masdar City, Abu Dhabi UAE (photos below)

Source: 2getthere

An important distinction of these example unmanned robotic (self-driving) APM transit systems is their operational dispatching "on-demand" when passengers request a trip. If a vehicle is not already at the origin point when the passenger arrives, one is dispatched to this station either with passengers that want to go that destination, or completely empty, much like how a bank of elevators works in an office building or hotel with many floors. Demand-response services that operate in ATNs demonstrate that small vehicles can make direct origin-to-destination trips with the same or better level of service as single fixed-route lines utilizing larger vehicles/trains that make mandatory stops at each station. The cost-benefit of such automated transit systems is critically linked to the fact that they do not have an employee dedicated to operating each vehicle. This on-demand travel feature is discussed further in Chapter 5 dealing with applying functional and operational capabilities of AV technology to public transit service.

Connected Vehicle and Automated Bus Systems –Test-bed locations for prototype CV technology evaluations have been deployed in Ohio, Michigan, and Arizona. The USDOT safety pilot in Ann Arbor, MI included CV equipment (here-i-am and driver assistance warnings) on a small group of transit vehicles during the year-long evaluation of the technology. CV technologies on transit vehicles are envisioned to have a significant near-term safety impact, with bus crashes having significant severity, typically with many injuries and major traffic congestion after effects.

Some applications, such as platooning or cooperative-adaptive cruise control, require both automated and connected components. Bus platooning as shown in **Figure 5** was first demonstrated by California's Partners for Advanced Transportation Technology (Caltrans PATH) in 2003 using the magnetic nail technology developed for the automated highway system in the mid-1990s. The project was known as the Vehicle Assist and Automation (VAA) research program, and the deployment reached full demonstration in 2009.

Toyota also demonstrated this capability of running bus platoons combined with automated steering during the 2005 Expo in Aichi, Japan (see **Figure 6**). Toyota presented this important achievement to the international transit community as the Intelligent Multimodal Transit System (IMTS) at the 2005 ASCE International APM/ATS Conference (Aoki, Hayashida).

	
Demonstration project in 2003 Source: Caltrans	Demonstration project in 2009 Source: Caltrans PATH

Figure 5. VAA Demonstration Project
Source: Caltrans


Source: Wikimedia, and: http://www.expo2005.or.jp/en/technology/imts.html)

Figure 6. Toyota IMTS Automated Buses

From these early demonstrations of unmanned robotic vehicles steering themselves and from past demonstrations of automated vehicles connected with other vehicles for platooning purposes (typically with a bus operator still sitting in the driver's seat), technology has advanced over the past decade to where vehicles will soon operate in a truly driverless mode – steering themselves, tracking their location with precise geo-coordinates, and knowing the specific path they must follow to any specific destination using high-definition digital maps. A new age of AV transit may be emerging although there are significant challenges ahead.

Lessons Learned from 50 Years of Automated Transit Systems

Half a century of experience with fully automated transit systems provides several lessons, and opportunities for AV transit technology applications in the next half century. To close the historical look at automated transit systems, the discussion below investigates several lessons learned.

Maturation of Technology – Applications of advanced transportation technology bring a high level of energy and anticipation of changes that will result in the world. Indeed, the continual steps in automation within this field have brought many changes to the way transit services are provided, and reduced the operational costs to provide these services. The following discussion identifies issues that could slow down the progress of implementation as the great promise of AV Transit meets the realities of actual deployment.

1. **Enthusiasm can outpace the maturation of automated systems' capabilities.** There are often many enthusiasts who see the great potential of automation in the field of transportation, and they push the dialogue to extreme promises of what can be accomplished. Often, the statement of the enthusiasts when challenged on the practicality of the wonderful vision is "certainly the technology developers can figure out how to solve perceived problems or weaknesses."

Realistic views of AV technology progress can be maintained by having progressive updates to studies like this NCHRP 20-102(02) working paper, which identify the successes and challenges faced by the research and development initiatives.

1) **Research and development of new technology requires major capital investments.** Cutting edge R&D of automation technology is very expensive, typically involving:
    a) Conceptual design development of components, subsystems, and integrating technologies
    b) Prototyping major elements and proof-of-concept testing
    c) Development of test facilities by public and public-private partnerships and conducting numerous trials to vet the system concepts, determine actual performance capabilities, and thereby find and resolve weaknesses in the original design
    d) Commercial product/system design with appropriate analyses and further testing
    e) Producing a complete pilot/demonstration project with safe operations carrying passengers in service conditions suitably representative of the promised deployment operating conditions
    f) Adapting the design to satisfy transit-grade specifications for system deployment can induce or reveal design flaws that are difficult and expensive to resolve when going beyond the initial proof-of-concept deployments

These R&D steps are very expensive when involving a complete operating transit system; and very challenging to successfully accomplish from a business perspective when the technology demonstration has competition fighting for the same funding sources, especially when the competing technologies are proven and known technologies that can provide service enhancements with little risk of failure.

The result is that new technology developers look for major project funding sources even when the design is in only the conceptual or prototype phase. Any possibility to use government's or investor's money to complete the design becomes a major factor in the fight for survival of the original technology development entity. And when partially developed technology is sold in whole or in part to other entities during securing additional development funding, the original "idea" people often leave the pursuit and other people assume the final stages of development initiatives. In the end, delivery of the actual product may not be consistent with the original concepts "sold."

A key industry segment that could resolve this potential deficit of capital investment is the major OEMs already active in the pursuit of AV deployment and which have historically played a role in the transit vehicle market.

1) **Partnerships are required to deliver a complete operating system.** Most transit systems involve integrating many different types of technology and construction, usually including the original technology developer (i.e., the vehicle system supplier), civil and architectural design firms, control and communication system integrators, construction firms, and often financial firms to address interim financing, bonding, and insurance requirements. Liquidated damages are frequently a part of large

transportation system projects, especially when the technology is new and still not completely proven in passenger service. The fixed facilities of guideways and station – typically grade-separated – have historically been an essential part of automated transit systems, and the largest cost has been associated with **constructing the civil works**. Because of this fact, the leader of the project implementation team is usually a large construction firm, and the original technology developer must typically yield control of the project deployment. This can potentially compromise the original intended development steps.

2) However, the new paradigm of automated transit systems operating along existing streets and highways with only limited civil works involved changes this mix of project team partners and the lead role could move to the vehicle system technology supply firm.

Hurdles to Deployment – Bringing advanced technology to the market place can face hurdles not apparent when the pursuit began. Several aspects of slowing deployment have been seen in the historical context of advanced transit system technology, such as:

1) **Funding regulations constrain sources of Automated Transit supply** – Transit system procurements within the U.S. which are made with grants from the FTA require a significant percentage of the system supply, including the transit vehicles, come from U.S. sources of supply. There are a variety of ways to satisfy the specifics of the "Buy America Act" requirements, but tracking and documenting all supply sources for system equipment and fixed facilities is a major hurdle that must be cleared for any federally funded transit project. Currently, there are no AV Transit vehicle suppliers based in the United States with any track record of successful deployment. This is a chicken-and-egg problem, since there are very few transit agencies purchasing AV transit systems (yet).
2) **Labor agreements may constrain fully automated operations** – Even when full automation is accomplished and there is no longer a need for operators or attendants onboard, there have been circumstances where labor collective bargaining agreements required a human operator be retained at the front of each train or onboard as an attendant.
3) **Owner/operator transit agencies want someone to backstop their risk** – Any new technology applied early in its development cycle requires a sharing of risk – both with respect to operating costs and liability. For a public transit agency or similar owner/operator to implement a major project, there must be either a willingness to self-fund the "insurance policy" necessary to cover implementation and operating cost budget overruns, as well as major liability claims when crashes or collisions occur. These risks could possibly be pushed to the system supplier team and/or the federal government.
4) **Acceptance by industry professionals and system operators will take time** – The acceptance of fully automated transit in the U.S. has been slow to take root. For most of the past 50 years, fully automated systems have only been deployed within or connecting to major airports, but have been rejected as a technology of choice for more conventional transit lines. This has appeared to be due to the opinion of many transit

professionals that automation was fine for "people movers" within a district or a major activity center, but not ready for application on a regional scale. Yet during the last 30 years, fully automated regional-scale metro systems have been built all over the worldi. The first urban system of a regional scale in the U.S. is schedule to begin passenger services in Honolulu, Hawaii during 2018.

5) **Public acceptance of automated systems takes time** – The uneasiness that a passenger can feel when riding in a vehicle with no human operator can be a factor in the public acceptance of the fully automated transit system. And major publicity over any crash or collision involving an AV vehicle of any type will add to this discomfort. Over time, as full automation of roadway vehicles becomes more common, this uneasiness will fade. However, as the automated system begins to operate in conditions perceived to be less "controlled" the acceptance can take some time to be resolved.
6) **Challenges of "Safe" system design requires extensive analysis and testing** – The transit industry's venture into full automation has historically been based on rigorous safety analyses that have been derived from the aerospace/military industry. In fact, for most of the past 50 years military specifications for system safety programs has been the principle reference used in AGT system design. When the U.S. military began to make changes that supersede MIL Std 882C with new versions that were more specific to military equipment, the ASCE committee that maintains the ASCE 21 APM Standards wrote their own version of the original MIL Spec – refer to Section 3 Safety Requirements, and Appendix A: System Safety Program Plan of ASCE 21-13.
   a) Further, the FTA has multiple documents providing guidelines for transit system safety programs and specific safety guidelines, requirements, and analyses. Standards and codes for fully automated guideway transit systems are also maintained by the International Electrotechnical Commission (IEC) and the European Union[15]. These standards embody requirements for safety programs and documentation, detailed hazards identification and resolution processes, and detailed safety analyses.
   b) New methods of safety design are also gaining momentum, such as the specification of Safety Integrity Levels (often called "SIL levels") within the design requirements.
   c) These levels of safety analysis and certification needed in fixed guideway and aerospace systems are beginning to be addressed in the vehicle automation development community[16].
7) **ADA mandates for Transit Systems are particularly difficult for fully automated systems** – Of major importance with respect to fully automated transit systems is the

[15]For example, IEC 62267 Automated Urban Guided Transport (AUGT) – Safety Requirements; IEC Technical Report 62267-2 AUGT – Safety Requirements Part 2: Hazard Analysis at Top System Level; and CENELEC EN 50126 - Railway Applications – The specification and demonstration of Reliability, Availability, Maintainability and Safety (RAMS)

[16] https://www.cs.unc.edu/~anderson/teach/comp790a/certification.pdf

U.S. government's enforcement of the Americans with Disabilities Act (ADA)[17]. This set of governmental regulations has specific requirements for many aspects of a disabled transit patron's ability to access public transit. Flowing from the ADA stipulations are specific requirements imposed on the automated transit system facilities, and the points at which passengers board and alight the vehicle. Stipulations include provisions for passengers in wheelchairs entering the transit vehicle safely without assistance; movement of wheelchairs within the vehicle; protections against blind or hearing impaired passengers being struck by a vehicle. A particularly challenging boarding area design provision is protecting disabled patrons from falling between vehicles when the vehicle/platform doorways are misaligned or when the platform edge is not properly protected.

Comparison of Automated Guideway Transit and AV Roadway Transit

To complete the historical discussion of automated transit systems deployed over the past 50 years, the discussion below provides initial comparisons between the characteristics of guideway transit systems (AGT/APM/ATN) and the characteristics of future automated roadway vehicle (AV) transit systems. These similarities and differences will evolve over the course of time, since the replacement of human control and operational management with automated systems will be progressively accomplished over multiple decades.

Similarities of Fully Mature AV Systems with AGT/APM Systems

- No on-board operator or attendant is required
- Systems perform the functions previously performed by human operators –:
    - Protect against unsafe operating speeds, avoid collisions, stop safely, and maintain a safe travel path at all times.
    - Protect the passengers from being hit by a vehicle when near their boarding location, or being subjected to unsafe jerk and acceleration.
    - Operate the vehicles along their path as prescribed by the supervisory system, while adjusting their operating speed in accord with driving circumstances.
    - Monitor the progress of the transit vehicles, direct the vehicles to adjust their performance or dwell at a designated location when warranted, and track the provision of service levels for passengers, adjusting vehicle dispatched into service to meet level-of-service criteria.
- Automated vehicles are placed in service or taken out of service automatically, with designated operating fleet requirements met in accordance with a prescribed schedule of services appropriate for the time of day.
- Travel information and service information are communicated to passenger automatically.
- Supervisory personnel located within the operations control center, and roving operations personnel monitor system operations and respond when necessary to

[17] https://www.access-board.gov/guidelines-and-standards/transportation/facilities/ada-standards-for-transportation-facilities

support passengers or intervene to restore operations quickly when service disruptions occur.

- Differences between AV and AGT/APM Systems
- No trackwork or switches are required with AV systems.
- Stations for AV system may be more cost-effectively configured with mainline bypass of an off-line station and reduced size of boarding platform areas.
- Reconfiguration of passenger service can be dynamically made through automated dispatching of vehicles in response to changing ridership demand conditions.
- Service disruptions of a single vehicle cannot block the operations of other AV units since each can independently maneuver around stalled vehicles.
- When ridership demands cease at a location or in general within the system, the vehicles stop moving to conserve power and energy, as well as to minimize operating vehicle miles.

These basic traits of AV technology applications to transit are developed further in Chapters 4 and 5 after the state of AV technology development is addressed.

Conclusions on Historical Context of Automated Transit Systems

The evolutionary progress of automated guideway transit systems can provide insight into the path that automated roadway vehicles will follow as the AV technology is progressively applied to transit service. AGT/APM systems have included diverse combinations of vehicle sizes, route and station configurations, and operational management strategies – scenarios that are also being envisioned for AV transit applications. The key element across all types of AGT/APM systems is that automation is fully integrated into all subsystems by applying “fail safe” design principles and associated safety analyses.

The lessons learned over the last 50 years have relevance to the eventual implementation of major AV transit systems on a large-scale. These lessons include challenges to implementation as the automation technology matures, the hurdles to deployment faced by multifaceted partners in major transit projects, and the complexity of designing a truly safe transit system accessible to all passengers including those with disabilities.

3. Current State of Automated Roadway Vehicle Technology Development

In this chapter we characterize the current state of automated vehicle technology development in order to determine where the current gaps and challenges lie towards adopting automation functions in Transit services. As a snapshot in time (December 2016) of a rapidly moving technology development landscape, this assessment of demonstrations and capabilities cannot be expected to be comprehensive nor technically precise. The intent is simply to initiate where activities and actions need to be defined and executed on our transit automation technology roadmap.

NHTSA/SAE Levels of Driving Automation

To frame the discussion of concept technologies, we first introduce the Levels of driving automation. AV operations have been classified into **Levels** by both the National Highway Traffic Safety Administration (NHTSA)[18] and the Society of Automotive Engineers (SAE)[19]. NHTSA adopted the SAE five levels of driving automation in its September 2016 Policy Statement[20].

As shown in **Table 2**, NHTSA/SAE Level 0 is non-automated operation. Level 3 is the highest level of automation which still requires a human driver to remain in the vehicle ready to resume the dynamic driving task at any point when the driving automation system requires this transition. And Level 4 is the level of automation that is most important for AV public transit applications over the long term, since at that level it will be possible to remove the employee from the vehicle which will be fully capable or driving itself within the transit service area to which it has been deployed.

NHTSA/SAE Level 5 is arguably most relevant for private automobile applications which allow the vehicle to travel anywhere in full automation of the driving functions that a human driver could travel. However, this highest level of automation is not required for the needs of public transit service, since by its nature all public transit service is provided within a defined service area.

For public transit operations it can be asserted that systems like Masdar City UAE ATN, CityMobil2, and EasyMile Shuttles are precursors of the future transit operating systems with Level 4 automation. Their vehicles can reposition without an operator in the vehicle and need no sustained driver vigilance to “take over” control as is required for Level 3. However, now they can only operate within a relatively small defined area at relatively slow speeds and only along predefined transitways. Refer to **Appendix A** for a description of three existing ATN systems using fully automated vehicles.

[18] http://www.nhtsa.gov/About-NHTSA/Press-Releases/U.S.-Department-of-Transportation-Releases-Policy-on-Automated-Vehicle-Development

[19] http://standards.sae.org/j3016_201401/

[20] http://www.nhtsa.gov/nhtsa/av/av-policy.html

The terms and acronyms used in **Table 1** excerpted from SAE J3016 are Dynamic Driving Task (DDT), Object and Event Detection Response (OEDR), Operational Design Domain (ODD) and Automated Driving System (ADS). For a more detailed discussion of these terms and definitions, refer to **Appendix B** for interpretation of SAE J3016 taxonomy and definitions relevant for AV public transit applications.

Table 1. SAE J3016 Rules of Human Driver and Driving Automation System by level of Driving Automation
Source: Society of Automotive Engineers

Level	Name	Narrative definition	DDT: Sustained lateral and longitudinal vehicle motion control	DDT: OEDR	DDT fallback	ODD
Driver* performs part or all of the *DDT						
0	No Driving Automation	The performance by the *driver* of the entire *DDT*, even when enhanced by *active safety systems*.	*Driver*	*Driver*	*Driver*	n/a
1	Driver Assistance	The *sustained* and *ODD*-specific execution by a *driving automation system* of either the *lateral* or the *longitudinal vehicle motion control* subtask of the DDT (but not both simultaneously) with the expectation that the *driver* performs the remainder of the *DDT*.	*Driver* and *System*	*Driver*	*Driver*	Limited
2	Partial Driving Automation	The *sustained* and *ODD*-specific execution by a *driving automation system* of both the *lateral* and *longitudinal vehicle motion control* subtasks of the *DDT* with the expectation that the *driver* completes the *OEDR* subtask and *supervises* the *driving automation system*.	***System***	*Driver*	*Driver*	Limited
ADS* (“*System*”) performs the entire *DDT* (while engaged*)						
3	Conditional Driving Automation	The *sustained* and *ODD*-specific performance by an *ADS* of the entire DDT with the expectation that the *DDT fallback-ready user* is *receptive* to *ADS*-issued *requests to intervene*, as well as to *DDT performance-relevant system failures* in other *vehicle* systems, and will respond appropriately.	*System*	***System***	*Fallback-ready user (becomes the driver during fallback)*	Limited
4	High Driving Automation	The *sustained* and *ODD*-specific performance by an *ADS* of the entire *DDT* and *DDT fallback* without any expectation that a *user* will respond to a *request to intervene*.	*System*	*System*	***System***	Limited
5	Full Driving Automation	The *sustained* and unconditional (i.e., not *ODD*-specific) performance by an *ADS* of the entire *DDT* and *DDT fallback* without any expectation that a *user* will respond to a *request to intervene*.	*System*	*System*	*System*	**Unlimited**

The CityMobil2 project is particularly noteworthy as a pilot project. The automated transit vehicle demonstration was deployed in multiple cities throughout the European Union, and pushed the envelope in the operating environment to include conditions that included some mixed traffic environments. This program demonstrated AV operations along limited routes using city streets where non-automated vehicles were also operating, as shown in **Figure 7**. One of the vehicle technologies that was developed during the CitiMobil2 project has now being redesigned and marketed as the EasyMile shuttle system. This L4 shuttle system shown in **Figure 8** has been deployed in a demonstration project near San Francisco, California at AV development facility called GoMentum Station.

Figure 7. CitiMobil2 Vehicle Operations in Mixed Traffic(source: CitiMobil2)

Figure 8. EasyMile Shuttle System at GoMentum Station (source: Easy Mile website)

Enabling AV Technology Features

Automated driving systems are composed of several components, principally sensors, actuators, processors, and artificial intelligence software, all of which are constantly evolving as system developers gain experience in operating AVs in test-bed and real-world environments. Communications is also introduced as a key technology feature important to automated operation. While Google and others have avoided connectivity to infrastructure as a *requirement* for Level 3 or Level 4 operation, there is no doubt that (1) communications from some type of operations center with an automated, driverless vehicle in the event of failure(s) is critical for human intervention (whatever that "intervention" might entail), and (2) communications from infrastructure on real-time status of traffic controls and unforeseen anomalous conditions nearby will improve the ability of the AV to navigate through the environment safely and efficiently. **Table 2** summarizes key technologies for AV operation across the following attributes:

- Hardware
- Software
- Standards
- Current activities and demonstrations
- Future directions

Our intent in this table is not to specify capabilities with technical precision, but to identify general state of readiness or use as of Summer 2016, as it relates to automation of transit vehicles.

Table 2. Enabling AV Technologies

Relevant Technology Attributes	Hardware	Software	Standards	Current Activities and Demonstrations	Future Directions
Sensors					
Radar and ultrasonic sensors (forward collision warning, blind spot detection, lane departure warning)	Commercial grade, reasonable cost, readily available and integrated with many production vehicles; multiple vendors	Individual sensors provide individual warnings to drivers (Level 0), many basic Level 1 systems in production vehicles today; few Level 2 systems available today (Tesla, Mercedes, Cadillac)	NHTSA considering notice of proposed rulemaking on standard feature for forward collision warning with automated braking (Level 1); OEM/Tier1 decision on specific tech	Demonstrations on bus fleets imminent – Washington State, San Diego; Imminent for transit; offered to Smart City Challenge recipient by Mobileye	Expected growth in next 5-10 years; form factors currently available for transit vehicles
LiDAR (360 situational awareness)	Industrial grade, expensive; limited field-of-view models cost less than spinning; non-spinning fusion systems in development; several vendors	Enables Level 3 / Level 4 demonstrations (Ford, Google)	Per Tier 1/2 suppliers	No known transit applications with LiDAR	Unknown; form factors for transit would likely consist of fusion LiDARs versus top-mounted spinning LiDAR scanners due to vehicle shape and size
Stereo/3D video (360 degree situational awareness)	Commercial grade; moderate expense; common limitation of visual spectrum; multiple vendors	Enables level 2 demonstrations (Tesla, Mercedes, Cadillac); 3D synthesis in development	Per Tier 1/2 suppliers	No known transit applications with Stereo video	Unknown; form factors for transit would likely require additional development from passenger vehicle models or adapted from freight applications

Relevant Technology Attributes	Hardware	Software	Standards	Current Activities and Demonstrations	Future Directions
GPS/Differential GPS	Commercial grade; moderate expense; Differential GPS needs roadside correction units; extensive vendors	GPS not deemed reliable enough for any AV Levels; Differential GPS correction units may enable Level 1-4	Common standards	GPS tracking on buses/transit is common; DGPS is uncommon; DGPS used in Caltrans PATH demos (~2005-2007)	DGPS deployment linked to CV safety applications / AV applications without magnet-following tech; no known transit specific needs
Dead Reckoning (inertial navigation)	Industrial/commercial grade; moderate expense; multiple vendors	Fusion with other sensors in development	Common standards from aviation industry	No known transit applications with Inertial Navigation units	Linked to demonstration with other sensors; no known transit-specific needs
Lane center following magnetometer	Magnets inexpensive ($30,000/mile); reader devices unstandardized but proven since 2003; multiple vendors	Enables Level 1-Level 4 operation	No known standards	Production systems and production ready technology; 1997 AHS; 2003 AHS demo with buses; CityMobil2; Lane County, OR; Navya demos; Production system at Masdar City, UAE; variety of additional suppliers	Significant growth expected in next 5-10 years as shuttles, campus circulators, first-mile/last mile services can operate with simple sensors and fixed routes; transit-specific technology
Controls					
Throttle/brake control	Mechanical and Drive-by-wire systems available; multiple vendors for passenger cars; few for buses	Enables Level 1-4 operation	No known standards	Available in production vehicles (light, trucks) today; no known bus availability except for shuttle vehicles like Masdar City, CityMobil2, etc.; active development for Washington State; no known demos for full size bus; production shuttles	Significant growth expected in next 5-10 years as shuttles, campus circulators, first-mile/last mile services can operate with simple sensors and fixed routes; application models need consideration of transit-specific vehicle performance characteristics

Relevant Technology Attributes	Hardware	Software	Standards	Current Activities and Demonstrations	Future Directions
Steering control	Mechanical and Drive-by-wire systems available; multiple vendors for passenger cars; few for buses	Enables Level 1-4 operation	No known standards	Available in production vehicles (light, trucks) today; no known bus availability except for shuttle vehicles like Masdar City, CityMobil2, etc. and Lane County Transit; active development for Washington State; Lane County Transit; production shuttles	Significant growth expected in next 5-10 years as shuttles, campus circulators, first-mile/last mile services can operate with simple sensors and fixed routes; application models need consideration of transit-specific vehicle performance characteristics
Object recognition / avoidance	On-board computer processor(s) for integrated sensor fusion; very few off the shelf options	Common and necessary across Level 1-4 applications	Depends on sensor type(s)	Difficulty increases as speed increases (time to detect and act decreases); common techniques from military/aviation are well-proven, but mostly proprietary; primary response is full stop (versus swerve); production-level development	Sensor fusion techniques will become more capable to determine differences between object types (e.g paper bags versus rocks)
Traffic control recognition	Commonly only done with vision systems today; map matching / geographic intersection description (GID) read	Limited success for visual with object recognition; map lookups for static signage; enables Level 3-4 operation	No known standards	Google; no other known system abilities to negotiate intersections in real-world; transit priority treatments for Citymobil2 vehicles	Nexus of CV/AV world; broadcast of signal status would simplify intersection operation; should develop strongly in next 5-10 years; near-term deployment using dedicated transit lanes simplifies this

Relevant Technology Attributes	Hardware	Software	Standards	Current Activities and Demonstrations	Future Directions
Car-following	Radar, LiDAR, Vision, DSRC;	Enables Level 1-4 operation	Variety of known and proven algorithms (simulation); Collision Avoidance Metrics Partnership (CAMP) is developing Cooperative Adaptive Cruise Control (CACC) standard operating procedure	1997 and 2003 AHS demonstration of buses; CAMP demonstrations; multiple truck platooning initiatives; adaptive cruise control on many production vehicles: CAMP, SARTRE, Peleton, 2003 AHS bus demo, others; production grade deployment with adaptive cruise control	Core algorithms should become smarter in next 5-10 years and with V2V communication; application models need consideration of transit-specific vehicle performance characteristics
Lane-changing	RADAR, LiDAR, video; multiple sensor fusion probably necessary; map matching;	Enables Level 2-4 operation	Variety of known and proven algorithms (simulation); no known performance standards	Tesla production vehicle Level 2; Google vehicle Level 3; other demonstration vehicles with similar capabilities; no known bus activities; emerging discussions of design standards / methodologies; no known transit demos	Core algorithms should become smarter in next 5-10 years and with V2V communication; application models need consideration of transit-specific vehicle performance characteristics
Merging	Radar, video, LiDAR; multiple sensor fusion probably necessary; map matching	Enables Level 2-4 operation	Variety of known and proven algorithms (simulation); no known performance standards	Emerging discussion of design standards / methodologies; 1997 and 2003 AHS demos; variety of OEM and Tier 1 supplier demos; no known bus demos	Core algorithms should become smarter in next 5-10 years and with V2V communication; application models need consideration of transit-specific vehicle performance characteristics

Relevant Technology Attributes	Hardware	Software	Standards	Current Activities and Demonstrations	Future Directions
Interaction with non-motorized modes	RADAR, LiDAR, Video	Higher level object recognition and behavioral assessment/prediction; recognition of hand signals	No known standards	Emerging discussion of design standards / methodologies; hand signal recognition; pedestrian and cyclist recognition (automated braking)	Core algorithms should become smarter in next 5-10 years and with V2X communication (if possible); application models need consideration of transit-specific vehicle performance characteristics
Path planning (passing, multi-lane changes, intersection negotiation)	Multiple sensor fusion needed; map matching	Enables Level 3 and 4 operation	Some algorithms available from simulation models; no known standards	Developer trade secrets; DARPA Urban Challenge; Google; PRT transit in small networks	Core algorithms should become smarter in next 5-10 years; application models need consideration of transit-specific vehicle performance characteristics
Route planning	Map matching; automated dispatch for PRT on designated route options	Enables Level 3 and 4 operation	Many algorithms available from route guidance systems	Developer trade secrets; some open PRT dispatch methods	Core algorithms production ready today; integration with path planning for Level 3-4 operation will take several more years; application models need consideration of transit-specific vehicle performance characteristics

Relevant Technology Attributes	Hardware	Software	Standards	Current Activities and Demonstrations	Future Directions
Communications					
DSRC On board Unit (OBU)	Currently expensive, 4-6 stable vendors	Proprietary/open-source (USDOT developed apps); 2nd Generation; implementation typically tied to HW platform; several models (simple broadcast, driver warning, automated action); some separation of radio from processor	5.9GHZ licensed comm channel; messaging standards for Basic Safety Message (BSM), Signal Request Message (SRM), others; additional messages proposed in 2015/2016); limited processor specification	NHTSA mandate for light vehicles imminent; no mandate for transit announced as of June 2016; anticipated shortly after (2019?) light vehicle announcement; Demonstration of V2V apps) on buses as part of USDOT Safety Pilot in 2013; USDOT Safety Pilot 2013; USDOT CVPD New York, NY, Wyoming, Tampa, FL 2017; Handful of additional test-beds in AZ, VA, FL, CA, PA, NY, MI; Buses will be included in NY/Tampa demos	NHTSA mandate should be shortly following CVPD site demonstrations (2018); Some uncertainty of ability of DOT to continue to protect band as licensed; 5G+ technology may supersede capabilities of ~2005 DSRC tech; CACC seen as critical application for nexus of CV and AV tech; antenna mounting needs specific consideration of transit vehicle shape/size
DSRC Roadside Unit (RSU)	Currently expensive, 4-6 stable vendors	Proprietary/open-source (USDOT developed apps); 2nd Generation; implementation typically tied to HW platform; some separation of radio from processor	5.9Ghz licensed comm channel; messaging standards Signal Phase and Timing (SPaT), GID, Signal Service Message (SSM); Basic Infrastructure Message (BIM) in development; limited processor specification	No mandate to DOTs to support V2I/I2V; V2I coalition (AASHTO/ITSA/ITE) focusing on roadway applications for curve speed warning, traffic signals (transit priority), queue warning, and work zones; Arizona and California test beds for Transit Priority with DSRC; USDOT Safety Pilot 2013; USDOT CVPD New York, NY Wyoming, Tampa, FL 2017; Handful of additional test-beds in AZ, VA, FL, CA, PA, NY, MI	Some uncertainty of ability of DOT to continue to protect band as licensed; 5G+ technology may supersede capabilities of ~2005 DSRC tech; RSUs required for intersection safety applications (red light running, cross traffic warning)

Relevant Technology Attributes	Hardware	Software	Standards	Current Activities and Demonstrations	Future Directions
4G/5G Long-Term Evolution (LTE)	Commercial grade very low cost; environmentally-hardened moderate cost; many vendors	typical separation of radio from processor	Open Standard comm protocols (IP)	More commonly installed in passenger vehicles and transit vehicles for infotainment/passenger access to Internet; 5G anticipated 2020; Many buses already have 4G hotspots; WiFi is sometimes used by AV shuttle services for remote monitoring and piloting	Continued provision of 4G connectivity on buses to drive ridership and enhance user experience; sharing of in-bus video with law enforcement
Low Latency LTE	Tech demo stage; 20ms latency; unknown expense; unknown transit form factor	Proprietary (Euro/Chinese demos)	Euro and Chinese V2I/V2V LTE-V standards work 3GPP	Research and Development stage; Euro/Chinese demos	Could have serious legs since uses existing infrastructure (cell towers) with only software/hardware updates
Mapping					
Sub-lane-level accuracy maps	Significant storage space and processing power needed for large geography; cloud-based connections to pull new maps	Necessary to enable Level 3 and 4 operations	No known standards although GIS descriptive languages for 3D models and CAD data are applicable; HERE has launched an effort to develop a standard format with OEM partnerships	HERE already publishes high-resolution maps for North America and Europe; could be called “beta” stage; Google mapping product forthcoming	May have significant traction to standardize map services from a few providers in 2-10 years versus proprietary implementations; will need transit-specific features for AV transit operations

Relevant Technology Attributes	Hardware	Software	Standards	Current Activities and Demonstrations	Future Directions
Infrastructure databases	Significant storage required for large geography coverage	Necessary to enable Level 3 and 4 operations	GIS standards are available, although significant variation in regional implementation and availability of up-to-date information	HERE, for one, planning a feedback structure from the AVs themselves to update the infrastructure map without need for coordination with 10,000+ agencies; could be called "beta" stage	May have significant traction to standardize infrastructure services from a few providers in 2-10 years versus agency-specific implementations; will need transit-specific features for AV transit operations
3D LiDAR point clouds and visual overlays	Significant storage space and order of magnitude more processing power than computer-aided drafting (CAD)-type maps needed for large geography; cloud-based connections to pull new maps	Sophisticated algorithms needed for effective use of technology; may be needed for "true" Level 4 "go anywhere" operation	3D image file formats are available from geographic information systems (GIS) and video game industries; scalability to significant geographies is challenging	HERE "HD live map"; could be called "beta" stage; Google mapping product likely forthcoming	Unknown yet if this level of technology is necessary for true Level 4 operation; no specific implications for AV Transit operations

Implications of Technology Readiness for Transit

Caltrans PATH work dating back to 2003 demonstrated several automated transit functions including automated platooning and automated steering on transit vehicles[21]. These prototype AV technology features were demonstrated in revenue service in Lane County, Oregon in a pilot deployment. The approach uses magnetic nails/markers embedded in the pavement along the BRT route (and did so as well in the freeway tests in 2003). The vehicle follows the sequence of markers to continuously calibrate its location allowing the controls to guide the steering to an extremely precise degree, including the ability to dock the BRT vehicle at stations with centimeter accuracy. Such existing path guidance technologies are highly reliable and relatively "low tech." They will be very valuable for high precision guidance in transit station berthing/docking areas. The Lane County demonstration did not utilize automated throttle control.

Sensors – Passenger vehicle technologies, spurred by the DARPA challenges in 2005-2009 have outpaced developments specifically targeted for general purpose transit operations. The integration of enabling technologies (sensors) for automated operation are just beginning to find their way into buses. As sensor technologies continue to advance, transit-specific versions will need to address bus-specific form factors for equipment installation, but also sensitivities, placement, field of view, and other parameters different for modern transit vehicles than for passenger vehicles. For example, spinning LiDAR scanners will not likely be effective mounted on top of a bus as the field of view is obstructed by much of the bus chassis. Sensor-fusion technologies will be necessary for safe operation of automated buses. Faster adoption of automation in the trucking industry may also drive these new form factors as truck chassis and limitations are more similar to transit vehicles than passenger vehicles.

Artificial Intelligence – Artificial intelligence algorithms also need further development specifically for transit applications. Buses do not respond the same as passenger vehicles to basic throttle and steering commands and have more challenging requirements for algorithms that merge a bus into a stream of vehicles, weave across several lanes of traffic, or execute left-turns in intersections, for example. It is not enough to just drop in an algorithm(s) designed for passenger vehicles (or trucks, for that matter) and automate transit vehicle operation. Significant work is necessary to modify the operating parameters of these methods for transit operation in general mixed-traffic environments. Algorithms in general are not currently at a state in 2016 where any developers' vehicles can drive all the way from a general origin to a general destination at Level 3 or 4. Rather, current demonstrations are generally testing vehicle operations along a selected set of predetermined, well-mapped routes. Moving from Level 2 operation to Level 3 operation is a significant technology move, more so for the artificial intelligence software and processing power (in our opinion) than for need of better and more capable sensor systems.

The low-speed shuttle mode operating at Level 4, however, has shown significant developments over the last five years with several systems in revenue service (Masdar City, Heathrow Airport and Rivium Office Park in Capelle, Netherlands – refer to **Appendix A**) and a

[21] http://www.path.berkeley.edu/sites/default/files/publications/PRR-2009-12.pdf

host of new pilot deployments coming online across the World. These vehicles work with existing guidance and control technologies by substantially simplifying the operating environment (and thus the complexity of their control algorithms) and lowering the speed to minimize the severity of failures. The significant opportunity for automation in transit is likely scaling up the technologies developed for low-speed shuttle operation to use on common bus form factors in dedicated environments, such as the BRT system in Lane County, OR. Building on this, additional automation functions can be added incrementally to allow more and more autonomy across more general environments. First in small networks of shuttle stops where the routes are protected from use by mixed-traffic and vehicles can use the proven technologies for route adherence (lane keeping and path following).

Communications – With communications, all shuttle operations require significant bandwidth and continuous communication links for remote monitoring and piloting in the event of vehicle system failures. Existing communications methods should be adequate for such operations and not impede any development of automation in transit services. There is no debate that CV technologies which link vehicles to continuous data streams the roadway infrastructure and from other vehicles about the operating environment can substantially enhance automated operations. There is nothing inherently precluding computers from ingesting data from existing CV concepts and acting on it automatically, except that in many cases some information transmitted is expected to be consumed by a human driver (particularly the general category of "traveler information"). This may include complex messages regarding route characteristics that a human could easily process with local knowledge of an area, but would need to be reduced to detailed updates to real-time maps, or meta-data about the map, or some command language easily processed with cognitive algorithms or natural language processing that are not mature as a general technology. More emphasis will need to be placed in the near-term on assuring that CV communications (messages and information, not the underlying transport technologies) are "AV ready" to facilitate connected-automation operations – not only for transit vehicles, but for AVs in general.

Mapping – High-resolution maps of the roadway network and street infrastructure are critical for enabling generalized Level 3 and Level 4 operation of AVs including transit vehicles. HERE has notably identified this as a market need and is beginning to offer this as a service[22]. Road centerline maps enabling route guidance for human-driven vehicles simply cannot be used by AVs for tactical negotiation of the roadway environment. On-board storage of such a sub-lane-level precise (and hopefully accurate) dataset is formidable and requires more than what can be easily stored on a $99 navigation device. The data regarding traffic control elements such as speed limits, stop signs, traffic signals, turn restrictions, and so on is a similar need for Level 3 and 4 operation and specific data relative to transit operations will be needed for general operation of AV Transit. Since these data are typically managed by a myriad of state, county, and local government entities today, a standardized database of all the infrastructure assets will almost assuredly need to be managed by a third-party(s) or the federal government. This is a formidable challenge to generalize operation of AVs at Level 3 and Level 4 across the U.S. and the world.

[22] https://company.here.com/automotive/intelligent-car/here-hd-live-map/

Conclusions on State of AV Technology Development

Some transit-specific technology development is still needed to enable AV Transit applications. Transit vehicle chassis size and operating characteristics will require specific sensor fusion approaches and developments in specific artificial intelligence systems. Challenges of technology development are not expected to be the limiting factor in adopting AV in Transit, but will need progressive demonstration of capabilities in test environments and deployment projects.

4. AV Applications in Transit Services

Application of AV technology will likely progressively find its way into transit systems. The rate at which technology penetrates the public transit market will certainly be paced by both public and institutional acceptance, affected by the regulatory environment that Transit must operate within. In this chapter we develop a timeline of potential adoption of AV technologies for operational Transit scenarios along surface roadways, and facilitated by the enabling technology readiness discussed in Chapter 3. These stages of development, roughly mapped to the NHTSA/SAE levels of driving automation, define the time and technology framework under which the necessary activities addressing regulatory challenges will be assigned in the roadmap contained in the Final Report.

AV Enabling Technologies and Transit Applications

Service applications of automation technology within transit vehicles is an important first definition of AV introduction to public transit. Subsequent chapters will address the associated ***facilities*** and ***operational considerations*** of AV introduction into transit systems. Table 3 illustrates the correlation of human/machine interface functionality, and transit vehicle capabilities with progressively higher levels of automation on the NHTSA/SAE scale. Refer also go the **Appendix B** summary of the NHTSA/SAE taxonomy and definitions regarding the dynamic driving task.

Table 3 is organized as follows;

1) **NHTSA/SAE Automation Level** provides a first level correlation to the AV enabling technologies matrix presented in Table 2. Definition of the NHTSA levels, and a correlations to the SAE levels of automation was provided previously in Chapter 3.
2) **HMI Operational Classification Level** provides a basic description of the human/machine interface (HMI) in each transit vehicle as the AV functions move from Level to Level. This indicates the level of responsibility, skill, and attention a human must maintain as the transit vehicle operates within its given operating environment.
3) **Example Automated Machine Functions** indicates a correlation to the AV enabling technology matrix of Table 2. Note that these are examples, since a comprehensive description is beyond the intent of this summary.
4) **Transit System Applications** provides a representative explanation of transit system application, without attempting to provide a comprehensive discussion.
5) **Potential Deployment Timeline.** Although timelines for deployment are difficult to forecast, the times indicated are a first attempt at assessing when a mature functionality for general transit use will be possible.

Note that the timeline for technical feasibility does not consider the separate timelines for institutional changes to operating policy, governmental agency regulations, and associated laws. These aspects will be addressed in subsequent working papers.

Table 3. Human/Machine Interface Functionality

NHTSA/SAE Automation Level	HMI Operational Classification Level	Example Automated Machine Functions	Transit System Applications	Potential Deployment Time Line
0 **No Automation**	Human-Driving	None	Conventional Roadway Transit Vehicles, No Automation	Today
	Human-Driving with Warnings	Forward Collision Warning (FCW), Blind Spot Warning (BSW), Lane Departure Warning (LDW)	Conventional Roadway Transit Vehicles with necessary sensors that provide warnings now and may enable Automation later	Today - 2020
1 **Function Specific Automation**	Human-Driving w/Machine Assistance	Adaptive Cruise Control, Lane Following, Emergency Braking (separately)	Safety-Enhanced Conventional Roadway Transit Vehicle	
			a.) Enhanced technology buses	2015-2020
			b.) Enhanced technology automobiles (e.g., ride-share vans)	2015-2020
2 **Combined Function Automation**	Machine-Driving in Special Environments for Enhanced Safety	Adaptive cruise control, automated braking, and lane following (together)	Advanced Technology Roadway Vehicles with Platooning with an Operator on Each Vehicle Monitoring the Automated Driving Functions	
			a.) Special Environment: Buses in HOV/managed lanes	2020-2025
			b.) Special Environment: Bus Rapid Transit in exclusive transitways with controlled at-grade crossings of city streets and pedestrianways	2015-2025

NHTSA/SAE Automation Level	HMI Operational Classification Level	Example Automated Machine Functions	Transit System Applications	Potential Deployment Time Line
3 **Limited Self-Driving Automation**	Machine Driving w/Human Oversight	Automated driving over portions of a route with substantive travel distances, but with human operator available to take control if required	Automated Operations Between Stations; On-Board Attendant (present for failure management and emergency incident mgmt)	
			a.) Special Environment: Buses in HOV/managed lanes	2020-2030
			b.) Special Environment: Bus Rapid Transit in exclusive transitways with controlled at-grade crossings of city streets and pedestrianways	2020-2030
			c.) Mixed Traffic Environment: Local bus routes and demand-response dispatch service on local city streets and arterials	2025-2035
		Automated driving with high precision maneuvering at low speeds	Automated Operations During High Precision Maneuvers; On-Board Attendant (present for failure management and emergency incident management)	
			a.) Station approach and docking maneuvers at platform berth	2015-2020
			b.) Precision maneuvering in storage areas or within maintenance depot	2015-2025

NHTSA/SAE Automation Level	HMI Operational Classification Level	Example Automated Machine Functions	Transit System Applications	Potential Deployment Time Line
4 **Full Self-Driving Automation**	Machine Driving w/o Human Presence Required; Provisions for Human driving operations by roving "recovery" personnel or by remote control from a centralized or nearby location	Automated driving, path determination and station berthing without a driver onboard at any time from origin to destination,	Automated Transit Route or Demand-Responsive Dispatch Operations; Empty Vehicle Repositioning/ Storage	
			a.) Special Environment: Protected (e.g., campus) environment on dedicated transitways at low operating speeds	2015-2020
			b.) Special Environment: Automated HOV/managed lanes with operator boarding at HOV/managed lane facility exit station stop	2025-2035
			c.) Special Environment: Bus Rapid Transit in exclusive transitways with controlled at-grade crossings of city streets and pedestrianways	2025-2035
			d.) Mixed traffic operations (i.e. interacting with other non-automated vehicles) at low speeds on city streets	2025-2035
			e.) Mixed traffic operations (i.e., interacting with other non-automated vehicles) at all speeds and in any roadway operating environment	2030-2050

Transit Functionality with Progressive Levels of Automation

Table 3 organized the transit vehicle functionality under progressive levels of automation. Chapters that follow will expand on the functionality as it relates to types of service and facilities impacted with this new paradigm of automation. The discussion that follows provides some examples of specific functional implications for the various levels as defined by the NHTSA/SAE classifications of automation.

NHTSA/SAE Level 0, No Automation – The definition by NHTSA/SAE is only with regard to the driving and throttle functions, and thus semi-automated functions like lane departure alerts or pedestrian warnings are considered Level 0. For example, alerts from the vehicle's automated controls that the vehicle is leaving the lane without a turn signal activated. Typically, this alert would be through means such as the steering wheel vibrating to immediately warn the operator even as the vehicle responds by realigning its trajectory with the lane. Lane-following warnings are currently being planned (for one) by San Diego Area Governments (SANDAG) for the prototype deployments of buses running in shoulder lanes in San Diego County, California23. Deployment of enabling technologies without automation may be an important interim step for transit agencies since there are minimal impacts of equipment, personnel, operating procedures, and policy/regulations.

NHTSA/SAE Level 1, Function Specific Automation – In the transit world, adaptive cruise control and lane following have been tested in the past, but have not yet been included in full operational deployment by major transit operators within the U.S. as of the end of 2016.

However, emergency braking functionality is being actively promoted, such as the initiatives in the State of Washington being led by the Washington State Transit Insurance Pool24. The immediate benefits to bus operations of all types can be quite easily justified through cost/benefit analyses that consider the frequency of bus crashes due to failure to brake quickly enough, and the average cost of these incidents versus the cost to retrofit buses with the new technology for automated braking prior to impact.

We foresee Level 1 automation features being deployed in the relatively near-term (2020) on new vehicles purchased with integrated equipment particularly for automated braking with forward collision warning sensors. This automation feature will not change any aspect of current driver functions and will hopefully be shown in trials during 2017-2020 that its inclusion will increase safety by preventing transit vehicle crashes. Funds otherwise spent by transit agencies on resolving claims will be redirected towards technology purchases with a positive return on investment. Adaptive cruise control and lane following functions will still require the vehicle operator to remain alert with "hands on the wheel" and ready to resume full manual control of driving functions at any time it becomes necessary. Regulatory issues that could be a factor will be assessed in subsequent working papers.

[23] http://www.sandag.org/index.asp?projectid=283&fuseaction=projects.detail

[24] www.wstip.org

One example of a bus operation under Level 1 automation was the BRT line demonstrated in Lane County, OR[25]. This bus system had automated steering, but did not have any type of automated throttle control (e.g., adaptive cruise control). The automated steering was performed by the bus equipment, but the propulsion and braking were controlled by the person sitting in the seat on the operator's platform. The lack of automated throttle control was primarily because, as with most transit services across the nation, the bus must interact with traffic signals along the route. While preemption and priority systems for transit are commonplace, they are not foolproof and similarly the technology for reliably communicating traffic signal status is still in development. Regulatory and liability issues related to this will be discussed in more detail in future Working Papers. The Lane County project vehicles followed magnetic markers within the transitway (typically called magnetic "pucks" or "nails"). The accuracy of the vehicle's position was so accurate that the vehicle berthing at each station is precise enough to control the gap between the door threshold and the platform edge in compliance with ADA requirements for automated guideway transit. Caltrans PATH demonstrated this precision docking technology in California in 2009 (see Figure 5 above for a photograph of the demonstration project).

NHTSA/SAE Level 2, Combined Function Automation – As enabling technologies become more thoroughly integrated on new transit vehicles, Level 2 automation will begin to allow full self-driving functionality in controlled environments such as protected/dedicated transit lanes. BRT lanes that are restricted from use by other types of vehicles are candidate transit facilities for Level 2 automation, such as the Orange Line BRT system that is operated by LA Metro[26] or the Lane County Oregon system. These facilities are prime candidates for application of the relatively simple magnetic nail technology since they are already designed exclusively for transit use and do not have (as many) real-world issues such as overhanging trees, drains, differences in road crowns from street to street, and miscellaneous street furniture unrelated to bus operations that bus drivers frequently negotiate on regular routes. Applications of Level 2 functionality for general bus operations are not anticipated to be acceptable from a technical standpoint, regardless of regulatory and policy challenges that will be discussed later.

Other applications of Level 2 capabilities will likely be coaches running in dedicated HOV lanes, or in some locations in managed lanes where other automobile are also operating with Level 2 or higher capabilities. Limited numbers of vehicles without AV features could be also operating within the managed lane environment, but maneuvering of vehicles in multi-lane configurations – such as with frequent merge and diverge slip lanes at high speeds – is likely to a condition prohibitive of applying Level 2 automation for transit vehicles.

One characteristic that will remain a reality while operating under this level of automation is that situations will occur when the automated controls require immediate return to full manual operations within a very short period (e.g., within five seconds). Further, the transition of the vehicle out of the protected environment of the HOV lane into mixed traffic flow conditions

---

[25] http://higherlogicdownload.s3.amazonaws.com/AUVSI/c2a3ac12-b178-4f9c-a654-78576a33e081/UploadedImages/Proceedings/Breakouts/Beyond%20Single%20Occ/VAA%20Presentation%20AVS%202015.pdf

[26] https://en.wikipedia.org/wiki/Orange_Line_(Los_Angeles_Metro)

where the automated features cannot safely retain vehicle driving control will require the operator to be fully alert and aware of the vehicle's operational surroundings to safely take manual control on very short notice. This transition of control at Levels 2 and 3 is one of the key areas of HMI research currently underway in the industry and further discussion of detailed technical aspects will be addressed with respect to potential regulatory issues in subsequent working papers27. However, with respect to the regulatory environment of the transit industry, these issues of transition from AV to manual are significantly more acute than for passenger vehicles given the increased level and complexity of liability that the driver, agency, and system providers face.

NHTSA/SAE Level 3, Limited Self-Driving Automation – When Level 3 AV technology is ready for application in transit service, the transit bus will be able to become a truly self-driving vehicle. AV's at this level of automation will be able to safely drive within protected environments while also navigating the driving path between a trip origin and trip destination (or a substantial contiguous distance where automated operation is not expected to be disengaged except for particularly anomalous conditions). While the vehicle is in self-driving mode, the onboard operator or attendant will be able to turn their attention to other tasks such as providing passenger assistance, customer relations, or travel surveys. As AV technology reaches this level of automation, the applications to BRT lines and dedicated HOV/bus lanes will have become common within the transit industry.

At this level of automation, low speed operations in mixed traffic along city streets will also become common using automated driving functions. When the automated system's artificial intelligence software becomes confused or when a key subsystem element fails, the alert to the onboard operator will allow sufficient time for the operator/attendant to take control and determine the operational conditions. This delay time may be 20 or 30 seconds to ensure the proper transition to manual operations. Alternatively, in the low speed environment of city streets, the automated controls may take the vehicle out of service at the side of the road (or simply just stop) until the onboard operator/attendant is ready to drive the vehicle around the fallen tree or negotiate whatever anomaly the software is not programmed to handle.

NHTSA/SAE Level 4, Full Self-Driving Automation – Level 4 AVs will not require any operator or attendance onboard. Level 4 Transit vehicles will be able to drive between any origin and destination along a path determined by either the transit operations supervisory control system, or by the vehicle itself supplemented by CV information flowing from other vehicles and the wayside infrastructure. We postulate that connected infrastructure information, principally traffic signal status data, is critical for safe operation of Level 4 vehicles (of all types, not only transit) in general mixed traffic.

There are currently prototype systems operating at several places around the world which have protected environments (e.g., campus-like pedestrian settings) or in very low speed traffic conditions and semi-protected operating lanes. However, the vehicles travel along very well defined paths and their locations are often determined from magnetic markers along the path. As GPS, sensor mapping, and artificial intelligence technology advances, these AVs will evolve

[27] http://www-esv.nhtsa.dot.gov/Proceedings/24/files/24ESV-000428.PDF

to operate in both low speed fixed-route settings and in higher speed mixed traffic (i.e., with other non-automated vehicles).

As AV capabilities reach full maturity over time, applications to general transit service in the form described in the next Chapter 5 will become possible.

Conclusions on AV Transit Applications

The progressive levels of driving automation identified by the NHTSA/SAE automation levels are indicative of the evolutionary path that automated roadway vehicle transit applications are likely to follow. Although not strictly true since some advanced AV applications representing Level 3/4 driving automation exist today in controlled environments and with limited capability guidance technology, the general progression of the NHTSA/SAE Levels of driving automation will apply for common roadway environments in mixed traffic operations.

The matters of operating agency policy, liability and insurance implications for operational transitions from automated vehicle control to human operator control is an area where further research is warranted from legal and contractual considerations. The related aspects of passenger “acceptance” of risk for public transit services when the human operator is no longer responsible for driving the vehicle is another area needing further research.

5. Potential Evolution of New Transit Paradigms

The conventional transit bus coach has evolved to the 40' bus size typically used today because it provides a good balance of cost-benefit when the bus is full (driver compensation, fuel, and other operating costs offset by transit fares). Similarly, the use of 50' to 80' rail cars has provided the backbone of transit service in high-demand travel corridors over the past century. But inefficiencies of many current transit systems result simply because the buses and trains are not full of riders over most of the routes route throughout the day. From the passenger's perspective, in many communities it simply takes too long to get from an origin to a destination as the transit vehicle/train makes many stops along the route, and transfers between one route and another add additional waiting time.

Further detrimental impacts to transit ridership are created when transit agencies invest in expensive line-haul systems on major routes with the objective of raising the benefit-cost ratio for transit, while creating the last-mile/first-mile connection problem in doing so. If transit vehicles can be made smaller and be deployed to operate in more of a point-to-point type service on roadways using demand-responsive automation like an ATN, we believe that trip times of individual patrons will likely become closer to private autos or taxis, bringing more transit users to the system. In the near- and medium-term, progressive levels of AV functionality as discussed in the previous chapter could address the first mile/last mile connection issues.

By removing the overhead cost of having an operator on every vehicle or train from the cost of fleet operations through automation, we believe the benefit-cost ratio of such an AV-based system could become an attractive option for transit agency investment, with the added stipulation that the regulatory and operational issues are addressed as discussed in further Working Papers. The FTA's current initiatives towards "mobility on demand" services for transit confirm that this direction of more nimble and personalized transit services is supported at the national level. FTA will certainly play a significant role in supporting this paradigm shift nationally.

Over the course of time we envision a wholly new concept of fleet operations in which route patterns may be changed. Although AV technology will certainly allow these fully automated operations described below, practical limitations of cost effectiveness and funding availability will certainly dictate what changes occur.

The following discussion of the near/medium-term future of AV transit reflects current trends in industry planning. The discussion of the long-term future is more imaginative in the concepts described. For all operational concepts described, there are of course significant engineering and infrastructure design implications of such operations, as well as political and regulatory inertia to overcome. These considerations of impact to and from policy, regulation, and laws will be discussed in subsequent Working Papers.

This new operational paradigm also has major implications for the way transit facilities can be configured and the way dedicated transit right-of-way will be determined. Stations in high demand travel corridors may conceptually change in their footprint and operations. The facilities aspects of off-line stations, parallel vehicle berths in stations, and storage areas in the immediate vicinity of stations characterized by high demand surge flow conditions are inherent to some of the long-term operational concepts discussed below.

The following discussion explores these new concepts of the future world of AV transit systems in a way that frames some of the issues addressed in the roadmap of activities related to regulations, laws, and technology. Equally important in the subsequent working papers are the implications for transit operators in their workforce deployment – both in terms of work assignments, and skills required to operate and maintain a progressively more automated transit system.

Near- and Medium-Term Operations

We posit that the earliest applications of AV technology to transit will involve the operation of buses as they travel along dedicated transitways such as exclusive BRT corridors, within high-occupancy vehicle (HOV/HOT) roadway facilities, or on existing Bus on Shoulder routes. In the near-term, these facilities can be upgraded to allow AV technology to autonomously steer the vehicles, perform propulsion and braking control, operate in multi-bus platoons, and provide collision avoidance protection.

AV technology will allow the BRT vehicles to be platooned (or “virtually coupled”) to create more train-like operation without the need for the track of an LRT, and likely at reduced cost with similar line-haul capacity. TSP has long been used to improve transit service in arterial corridors, but is continually criticized for the effects on side-streets when bus headways are relatively short. Virtual entrainment may be beneficial since it could provide a reduced impact on traffic operations by prioritizing traffic signals potentially less frequently, considering the caveats of stop location and potential revisions to stop capacity to handle additional buses at the same time. **Figure 9** shows a platoon of automated buses demonstrated in 2005 at the Aichi World Exposition by Toyota[28].

Another aspect of virtual entrainment was also demonstrated at the Aichi Expo. The “trains” of automated buses could add a new vehicle at the back of the platoon or disconnect a trailing vehicle while the platoon was moving along the transitway. This concept of dynamically reconfiguring a train of AVs is also being pursued for commercial trucks in the U.S. and Europe with serious emphasis on near-term operation due to cost savings due to fuel efficiency [29]. Anti-platooning and close-following laws in several states are critical regulations that need to be addressed (not only for trucks, but for buses in BRT lines) and a new research project addressing these legal constraints is needed.

Another development expected in the near-term is the blending of the previously developed and demonstrated guidance technology using magnetic markers with rapidly advancing high accuracy GPS technology and high-definition maps. The Toyota IMTS automated bus technology shown in **Figure 9** illustrates this type of bus guidance accomplished using magnetic markers in the roadway surface. The combination of these technologies allows the vehicles to operate in a free-ranging mode along some of the route using GPS, sensors, and

[28] http://www.apta.com/passengertransport/Documents/archive_1412.htm

[29] https://www.eutruckplatooning.com/About/default.aspx

localization of their position on the HD-map, but then in the immediate vicinity of station stops using the magnetic marker technology to provide extremely accurate and reliable docking and route alignment. Refer also to the description in Chapter 2 concerning Vehicle Assist and Automation (VAA) system (developed by PATH/Caltrans). As demonstrated in that research and development program, the accuracy by which the vehicle could steer allows the doorway thresholds to be in very proximity to the station platform edge – close enough to meet ADA requirements currently defined for fixed guideway systems. This topic is addressed further in Working Papers #4 and #5.

Figure 9. Toyota IMTS Automated Buses Following Magnetic Markers in the Roadway Surface at 2005 Aichi Expo

Source: Wikimedia

We believe over the medium-term, reserved lanes along freeway and tollways that include HOV and tolled/managed lane infrastructure will see a gradual implementation of both AV buses mixed with advanced AV private automobile operations. Bus on Shoulder operations are premium examples of potential AV operation as well. As noted previously, these controlled environments for AV transit operation will require transition zones where the vehicles return to fully manual operation before entering mixed traffic operations until such time that the automation has fully matured to Level 4 capabilities.

We believe the second context for early transit deployment of L4 AV transit will be in campus-like settings where there is a semi-controlled environment in which vehicles can operate at relatively slow speeds. This environment is commonly found in college and university campuses, large medical complexes, and master-planned communities where a transit vehicle operating at reasonably low speeds can interact with other traffic, pedestrians, and cyclists at low risk of injury or crashes. This scale of deployment has already been accomplished in the

CitiMobil2 project conducted by the European Union, including limited operations on roads with mixed traffic and basic traffic signals as well, at very low speeds[30].

As collision avoidance, object/person detection technology, and automation control algorithms continue to evolve and become more accurate and capable of handling more complex situations, speeds can be increased and a wider range of roadway facilities can be navigated. These evolutionary steps will probably take more than 10 years to be safely implemented.

Also suitable for near-term deployment in campus environments will be supervisory control features where vehicles can be dispatched in response to demand patterns and to specific person-trip demand requests in real time. This would include the redistribution of empty vehicles to high-demand points in anticipation of demands, thereby reducing transit passenger waiting times.

For the medium-term, the capabilities of AV technology in transit applications will gradually progress to allow the driverless L4 vehicles to operate in less controlled environments, such as city streets surrounding the campus complex, the major activity center or the subregional area originally served by the transit network. At this point in the evolution of the new paradigm in operations, the opportunities for first mile/last mile transit service will be realized and significant benefits will be obtained for overall transit ridership increases as high-demand travel corridor transit will be integrated with feeder/circulator systems within urban population/employment centers, major activity centers, and campus settings for medical/commercial/university environments.

Long-Term Operations

Operating concepts may pass through a complete paradigm shift during the long-term development of AV transit applications. In fact, the flexibility of future transit systems that respond dynamically to changing demand patterns will likely gradually begin to replace many, if not most fixed route transit operations.

As an example of this paradigm shift is the conceptual conversion of fixed guideway LRT systems to multiple physically or virtually entrained AV rubber-tire roadway transit vehicles as a BRT line. Conceptually, the future world of AV transit technology could allow the same vehicles to operate on some combination of dedicated transitways and/or conventional roadways while operating along their assigned travel path. In this potential future, a fleet of smaller automated transit vehicles could also be dynamically repositioned through strategic distribution anywhere in the transit network to serve changing demand patterns. Of course, this is just one possible vision, but one that seems particularly possible with the evolution of enabling AV technologies through the Levels we presented in the previous chapter.

Recent operational studies and concept development within the AGT/APM sector have developed such concepts with demand-response operating principles. By removing the cost of the guideways as technology becomes more mature, the future world of transit could provide a very high level of “customized” service to serve the needs of even large regions. In the long-term (perhaps with more than 30 years of progressive development), large-scale regional

[30] (http://www.citymobil2.eu/en/

transit systems designed around this demand-responsive/adaptive service concept may no longer require long trains operating on fixed routes that stop in all the equally large stations as they travel along a fixed route corridor[31]. In their place, dynamically configured “trains” of fewer, smaller vehicles – many of which within the same “train” consist may have unique ultimate destinations – can move efficiently through the high-demand transit corridor without requiring all passengers to stop at all intermediate stations along their specific travel path within the public transit system.

Demand-Response Dispatching has been performed for many years as part of transit bus services for rural and disabled transit patrons. These demand-response services typically have required a 24-hour advance reservations, although computer-aided dispatching has significantly reduced these response times utilizing internet and smartphone applications. However, in the long-term operational paradigm when many hundreds of transit vehicles of all sizes are in service and there will be a need for “real-time” dispatching with limited “man-in-the-loop” intervention. As in AGT/APM systems, the control system operator(s) will act as a monitor for safety and security of existing services, manage vehicle removal from service for repair activities, and provide customer service responses to passenger calls from stations or within the transit vehicles. The automated supervisory control system will manage the vehicle dispatching to match the trip patterns of pick-up and drop-off for all riders, make route assignment of vehicles, and will constantly communicate with all connected transit vehicles moving through the network or on-standby in storage areas. The composition of the transit agency employee staff will likely be much different in 30 years than it is today if automation technology is embraced.

It is likely that the typical transit services during busy times of the day will include multiple riders bound for the same destination from the same origin or with a limited number of stops for pick-up or drop-off on a common route. We believe the difference from typical fixed route, line-haul transit operations today will be the more direct origin-to-destination station service with fewer stops along the travel path of every transit patron. Transit users will have a travel time that closely matches the personal automobile.

Empty Vehicle Management is a corollary to real-time demand-response dispatching, since during significant periods of time (e.g. at night) there will typically be many fewer trip requests than during the peak periods. During those off-peak times the automated supervisory control system will send empty vehicles into storage locations placed throughout the transit network, typically near the portions of the transit network where high demands will arise during the next peak activity period. Then as trip requests are received, the supervisory system will dispatch a nearby and available empty vehicle to pick up the transit patron(s). It is this functionality that optimizes the use of energy and vehicle-miles by automatically removing vehicles from service as ridership demand drops.

Dynamic Route Reconfiguration is envisioned to utilize the flexibility of virtual coupling to reconfigure “trains” of vehicles as they enter or exit a station. **Figure 10** shows a vehicle that arrived at the station as an independent vehicle, and then it is automatically entrained with other vehicles by virtually coupling the new consist “on-the-fly” as the vehicles exit their station

[31] http://ascelibrary.org/doi/abs/10.1061/40766(174)31

berths. This type of dynamic reconfiguration of routes and vehicle pairing provides high flexibility by which the automated supervisory control system will continually optimize operations.

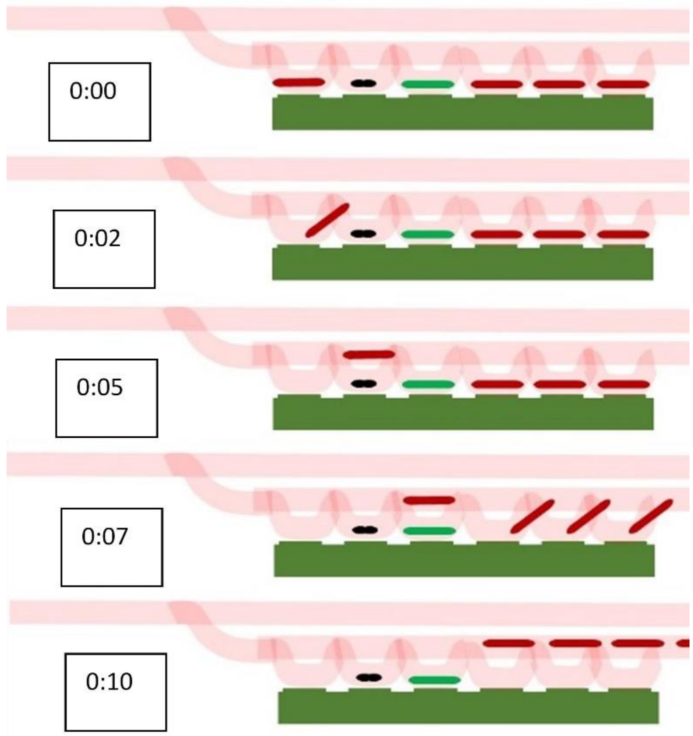


Figure 10. Concept of Dynamic Reconfiguration of Trains

And ultimately, as envisioned by past thinking of how even very large transit systems with very high travel demand corridor service like San Francisco BART or New York CTA systems, the ability of dynamically reconfiguring "trains" through virtual coupling concepts will reduce the length of trains and the corresponding station length/size requirements[32]. The ultimate demand-responsive operations will be possible for even the highest demand corridors of the largest transit properties when dynamic consist reconfiguration is combined with vehicles (or sets of vehicles) serving specific origins and destinations moving through a high demand corridor. With the station configurations as off-line stations that allow vehicles/trains to bypass intermediate stations that are not designated destinations for any passengers onboard, the transit patrons destination is literally the "next stop", just a "few stops away" no matter how long their total travel distance.

Mixed Route / Dispatching Operations allows the mixed service of demand-response, fixed route, and dynamic route reconfiguration, as well as various vehicle sizes to all be served from a common station. **Figure 10** above illustrates a station with vehicles of several sizes, the smallest vehicle (black) having arrived with a single party onboard that traveled directly from an origin station within the network to this destination station. The larger independent vehicle

[32] http://ascelibrary.org/doi/abs/10.1061/40766(174)31

(green) has also arrived in a demand-response mode, but with multiple travel parties onboard. The vehicles that are entraining (red) are all bound for a common station stop downstream in the network, but not necessarily the very next station on the line since the entrained vehicles may bypass that station stop.

Potential Near and Medium Term Changes to Fixed Facilities

The changes to transit facilities in the near term necessary to accommodate the new operational concepts for Levels 3 and 4 automated vehicles will begin to impact both conventional roadway and guideway transit facilities. The challenges of full automation and facilities that comply with safety and ADA requirements will be particularly challenging, particularly for locations that are planned to be built in the next 10 years. Some considerations of facility impacts are discussed here.

Transit Stop Locations – In general, as transit operations begin to employ on-demand features that allow the transit users to create more customized trips, the number of locations where transit service can be accessed could increase. This also brings consideration of an increase to the number of weather-protected shelters at new transit stops.

With the origin/destination options increasing from what is provided today with conventional on-demand public transit service, the realities may include the need to provide enlarged zones for public transit vehicles to stop adjacent to or within high-demand trip generators like urban districts, university campuses, high capacity rail stations and airports. Adequate provisions for protected boarding and alighting need to be provided for the number of large and small transit vehicles that may “swarm” during high activity periods.

Transition Zones at Protected AV Operating Environments – Early applications of Level 3 automated driving within protected environments like HOV/managed lanes of shoulder lanes will necessarily require the transit vehicles to transition back to primarily manual control as the vehicles leave the protected areas and enter mixed traffic operations still with perhaps Level 1 or Level 2 features available to the driver. These transition zones may eventually be possible while the vehicle is moving at high speeds, but for the near term the provision of a transition zone where the vehicle can be brought to a stop or substantially reduce the operating speed is likely to be necessary while the transition occurs. This could improve the possibility that the operator is fully aware and able to assume full operational responsibility. As an example, if the HOV lane has off-line park and ride facilities, this may be a good location for these transition zones. These kind of hand-off issues are likely to be particularly challenging from a regulatory perspective.

Multi-Berth and Off-Line Stations – Transit station facilities in the near term will begin to change from the conventional RT and fixed guideway station configurations. Starting in the near term, the functional ability to platoon AVs in multi-vehicle consists will immediately require BRT stations to accommodate multiple vehicles simultaneously stopping in each station along the line. This is the most eminent functional capability that will impact the conventional configurations of existing bus rapid transit facilities.

In the intermediate term, conventional on-line stations, at which all vehicles/trains passing along the main line transitway must stop at every station to allow any passengers to board or alight each vehicle/train, will gradually be replaced by off-line stations. Many vehicles (or virtual trains of vehicles) will bypass many stations without stopping since the transit supervisory system will know if any passengers need to board or alight at each stop. **Figures 5** above in Chapter 2 shows this type of off-line station as it was designed at the 2005 Aichi Expo, and **Figure 10** in this chapter illustrate the concept, as well. Since there will not be a need for switches or tracks with AV rubber tire vehicles, this configuration is much more practical to include. As a result of the tremendous flexibility from the new AV system equipment and off-line station facility configurations, new operational paradigms will be possible.

Near to medium term changes necessary to the design of transit fixed facilities should be studied in more detail through research activities that explore features and right-of-way requirements for station/stop location, transition zones from the main operating lanes into off-line stations, and the configuration of multi-berth boarding positions.

Potential Long-Term Changes to Fixed Facilities

Most or all the AV technology operational capabilities that is described above will be proven out in small scale demonstration projects in the near-term. In fact, many of the automated operating capabilities discussed here have already been demonstrated, and the private vehicle manufacturers, suppliers, and technology giants will continue to invest in the technology because they believe that consumers will buy these products. Even with rapid research and development of AV technology, however, the changes required to roadway infrastructure, governing laws and regulations, and transit operating agency policy will probably delay transit applications of AV technology for a time. As has been learned from the 50-year history for maturation of AGT/APM technology, it will take a long time for AV technology with autonomous vehicles in transit service to be commonly used as system equipment with new facility configurations, and with fully automated transit system operating capabilities.

Parallel Berth Stations – As shown in **Figure 11**, when each vehicle can operate autonomously from the rest of the vehicles and each vehicle can easily maneuver without physical guidance by trackwork, then there is the potential for off-line stations to be much more cost-effective to build since will be no guideway switches involved in accomplishing the merge/diverge operations. This is a radical change to the equipment currently needed in today's fixed-guideway systems. Further, vehicles will be able to maneuver into independent vehicle berths – even if as shown in **Figure 11**they enter the off-line station as a "virtual train".

This virtual coupling and dynamic entrainment is a fundamental automation component of achieving the level of service of today's existing fixed-guideway systems, potentially using smaller AV vehicles with higher passenger load factors. As such, it will have to be shown that abandoning fixed-route and fixed-guideway services appears cost-effective in near- and medium-term experiences of transit agencies with intermediary AV transit services, before we would expect that transit agencies would standardize on smaller AV transit vehicles completely. There is a need for more research in this area to demonstrate that this could be a viable future. Even such, it is not likely to be realistic for 20 or more years.

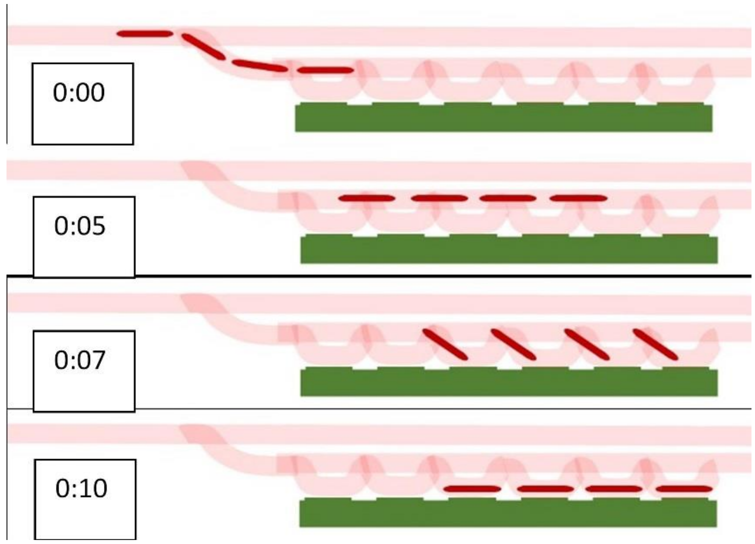


Figure 11. Virtual Coupling and Uncoupling of Vehicles Allows Individual Vehicle Berthing in Stations

Platform Edge Protection – An important aspect of automated vehicles and other system equipment concerns the station and equipment designs necessary to ensure the safe boarding and alighting of all passengers, especially those with disabilities, the elderly and small children. It is noted that typical station equipment for AGT/APM transit systems has generally incorporated fixed platform edge partitions and automated station doors. Worldwide, several notable metro systems with fully automated train operations have recently begun retrofitting platform edge doors into stations originally built without these functional elements. **Figure 12** shows the platform edge partitions and doors that were retrofitted in all stations on the Paris Metro Line 1 system while it continued to carry 750,000 passengers a day.

Figure 12. Platform Edge Partitions and Doors Retrofitted on Line One of the Paris Metro
Source: Paris RATP

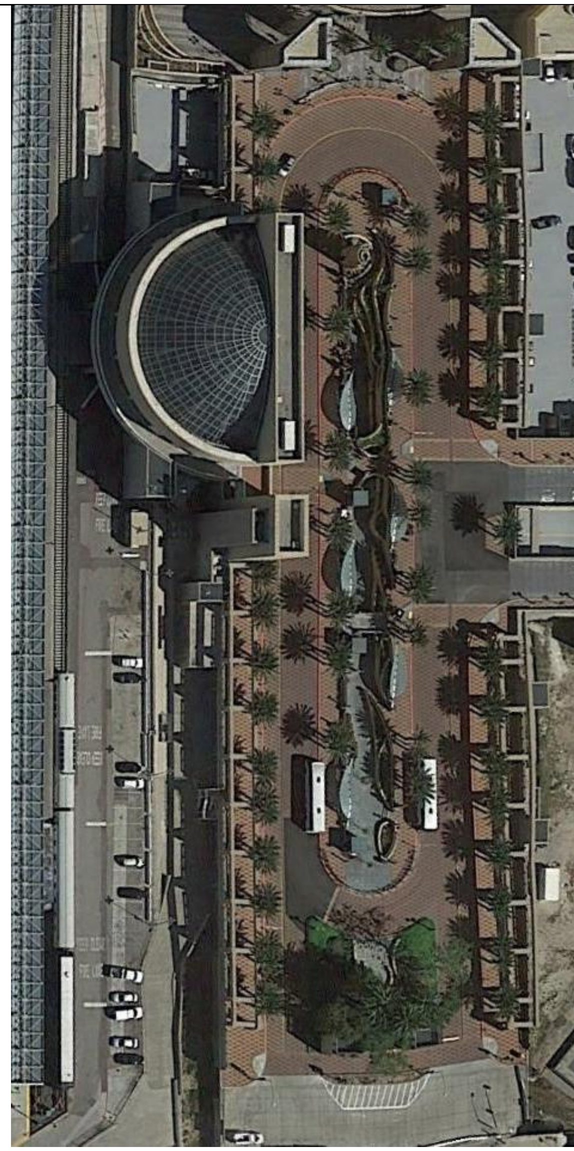
As shown in **Figure 13** the Toyota IMTS automated bus system at the 2005 Aichi Expo operated with buses making precise stops at each station, aligned with platform edge doors. Safety analyses and the ability of the robotic AV vehicles to monitor and safely confirm that all passengers have fully entered or exited the vehicle will determine the need for such platform edge protection in the future world of AV automated transit systems. This remains a question for the long-term research and development process to resolve, but the possible need to accommodate this functional element in high demand stations should be considered.

Figure 13. Station with Platform Edge Doors at 2005 Aichi Expo
Source: Wikimedia

Station Configuration – The implications of these future station configurations are that the number of guideway lanes and associated station footprints will grow *wider* due to the combined benefits of mainline bypass of the off-line station, especially when combined with the provision of a station passing lanes around parallel berths. However, with the changes to operating concepts as described above, most station *lengths* will shrink to a fraction of their current fixed guideway platform lengths. These long-term future operating concepts will allow individual vehicles and shorter groups of entrained vehicles to provide sufficient capacity to serve the same or even greater ridership demands at any given station location. When service patterns are changed to fit specific station demand patterns using fully automated trains, we have discussed in previous work that short trains on close headways are a much more efficient way to operate a transit system[33]. Stations with platforms that currently serve long trains will evolve to be configured more like those shown in **Figure 14**.

[33] http://ascelibrary.org/doi/abs/10.1061/40766(174)31

El Paso Sun MetroDowntown Transit Center



Los Angeles Union Station

Figure 14. . Off-Line Station Configuration with Individual Vehicle Berths
Source: Google Earth – El Paso, Texas; Los Angeles, CA

Maintenance and Storage Facilities – Maintenance facilities for AV automated transit systems will be configured much like conventional bus maintenance facilities, whereas the storage facilities can be located anywhere that is accessible to the route. Storage areas placed in locations away from the maintenance facility will be dynamically utilized throughout the day. Each storage facility's strategic placement and capacity will be designed to hold a portion of the operating fleet in a "hot standby" mode, until such time each vehicle is dispatched back into passenger service.

There will still need to be storage in or near the maintenance facility, since each vehicle will need a pre-service checkout and test, as automated guideway transit systems go through today. However, remote diagnostic checkout of all functions of vehicles will likely be possible due to existing wireless communications and software technology (e.g. Tesla vehicles and many other OEM vehicles get software updates over the air in 2016[34]), thus eliminating the need to size the maintenance facility storage areas to hold the whole operating fleet. In addition, the concepts of ATN system operations with vehicles held on-line during periods of dormancy – typically in parked station berths until they are dispatched into service as passenger on-demand activity increases – can allow the supervisory control system to optimize power and energy use, as well as minimizing vehicle-miles of use. Further," ready-vehicle" storage areas may also be provided for one or two vehicles that are in active service and awaiting dispatch, or possibly many vehicles at locations strategically placed throughout the network to accommodate high demand locations when necessary. Note that these ready-vehicle storage areas are not the storage areas needed at the maintenance depot where vehicles are removed from service.

Conclusions on Future Operations and Facilities

AV technology will be commonly applied in public transit service in the near and medium term. NHTSA/SAE Levels 2 and 3 driving automation will certainly be applied to provide self-driving functions in controlled operating environments such as HOV lanes, BRT transitways and low speed roadways. Over the long-term, automation of all aspects of the operations will become possible, exceeding levels of complexity currently existing in the most advanced automated guideway transit systems.

After AV transit operations at Level 2 are demonstrated and are in common revenue service, it will likely become clearer that fleets of smaller vehicles are economically more viable than the current operating practices of transit agencies today. This may change the way that transit service is viewed, and may lead to a greater interest in providing service geared for "mobility-on-demand".

If full automation of AV roadway vehicle transit systems does occur, a major paradigm shift in operations could also occur. However, the practicality and cost effectiveness of the long term conceptual operations may determine the pace of change to public transit in most places. Ultimately, the timing of operational and facility changes will probably be paced more by factors other than strictly technology. The time required for operational policy changes, regulatory changes and modification to laws and ordinances which *allow* automation to be implemented in public transit service may modulate when AV transit deployment occurs, and not technology capabilities.

[34] http://arstechnica.com/cars/2016/01/finally-over-the-air-software-updates-for-your-car-are-becoming-a-reality/

6. Summary of Deployment Scenarios and Timeline for AV Transit Technology Readiness

The discussion in this working paper has addressed a variety of transit service scenarios which will be possible with fully automated vehicle technology, combined with automated monitoring, management and dispatching of the operating fleet using a supervisory control system like that used by existing automated guideway transit systems.

The various AV transit technology deployments that will evolve over the near and medium term will be less advanced in levels of automation than will be the case over the long-term. The full vetting of each aspect of vehicle driving, autonomous path finding and inter-connectivity with other vehicles and the roadway infrastructure, combined with the automation of the passenger safety and accommodation in boarding, will probably take several decades to complete. For the long-term, the transit service envisioned involves more of the operating system's automation, than it does the individual vehicle's automation.

The following basic "functional" capabilities are introduced here, and then discussed in terms of progressive deployments in the summary that follows.

1) Protected (e.g., campus) environment on dedicated transitways at low operating speeds.
2) Bus Rapid Transit in exclusive transitways with controlled at-grade crossings of city streets and pedestrianways.
3) Automated HOV/managed lanes with operator assuming control of driving at HOV/managed lane facility exit station stop.
4) Mixed traffic operations (i.e. interacting with other non-automated vehicles) at low speeds on city streets.
5) Mixed traffic operations (i.e., interacting with other non-automated vehicles) at all speeds and in any roadway operating environment.
6) Fully automated transit route or demand-responsive dispatch operations, with empty vehicle repositioning/ storage as well as energy and mileage optimization

It is important to acknowledge that the deployment scenarios discussed below represent an assessment of the timeline for AV *transit technology readiness*. However, this timeline for technical readiness may not be the actual timeline by which policies, regulations and laws allow widespread deployment throughout the public transit industry. These policy and regulation aspects and their corresponding timeline are addressed in subsequent working papers.

AV Transit Technology in Current Applications – 2016

Currently there are a few limited demonstrations of AV transit technology operating in the world, ranging from Level 0 to level 4 driving functions as defined by NHTSA/SAE.

- Fixed route systems – Several demonstrations around the world, but operating at very low speeds in mixed traffic, and slightly higher speeds in exclusive transitways[35].
- Driverless vehicles following magnetic marker guidance systems (e.g., Lane County, Oregon bus operations, RIVIUM 2getthere L4 automated vehicles, and a few entertainment theme park rides). See **Appendix B**.
- On-Demand driverless vehicles with prototype GPS guidance at low speeds[36]

AV Transit Technology Ready in the Near-Term: Next 5 – 10 Years

Ongoing R&D efforts by OEMs software/robotics companies and federal/state departments of transportation have set a course that will produce AV technology fully capable of the following deployments within controlled operating environments and/or lower operating speeds.

- Deployments in controlled operating environments of:
    - Exclusive transitways (e.g. BRT) with self-steering vehicles, and with operator onboard.
    - Driverless applications in controlled environments at low speeds with driverless vehicles (e.g., campus setting).
- Subsystem Prototype development necessary to support deployments:
    - Vehicles operating in entrained platoons over portions of the operating “route” with virtual coupling and uncoupling with vehicle operator onboard.
    - Prototyping of automated supervisory control and dispatch operations.

AV Transit Technology Ready in the Medium-Term: Next 10 – 15 Years

Beyond the next decade, AV technology will begin to have deployments of the type that the AV development community has long anticipated.

- Deployments in HOV/ Managed Lanes and exclusive transitways (e.g. BRT) with Driverless Vehicles with operator/attendant on-board for quick response assuming the driving functions when transitioning to route segments running on higher speed freeways in mixed automated/unautomated traffic conditions.
- Deployments on fixed routes along city streets and arterials in Mixed Traffic at Moderate Speeds (45 mph or less) and With Driverless L4 Vehicles.

[35] CitiMobil2 has demonstrated AV operations at speeds of 20 km/hr for protected transitways with pedestrian traffic only, and 10 km/hr in mixed traffic along local streets in the European cities conducting the demonstrations. http://www.citymobil2.eu/en/Downloads/Public-deliverables/

[36] Singapore Autonomous Vehicle (SAV) Initiative has small battery-powered “golf-cart” vehicles operating within a park, providing on-demand dispatching of vehicles to travel requests initiated by mobile phone app, and destination selected by passengers onboard the vehicle after pickup. Source: Presentation at 2016 TRB Annual Conference by Emilio Frazzoli, MIT project manager for the demonstration project.

- Deployments in demand-response service within a network system configuration for fully automated transit vehicles operating along city streets/arterials in first mile/last mile circulator applications.

AV Transit Technology Ready in the Long-Term: Next 15 – 30+ Years

It will be technically feasible within a few decades to operate automated roadway vehicles within fully automated transit systems in full compliance with ADA requirements. These concepts may or may not prove practical for deployment overall, but aspects of the following AV transit operations will gradually change the existing public transit paradigm.

- Deployments with fully automated L4 transit vehicles operating in pure demand-response dispatched mode within a network configuration of the regional transit system.
- Deployments with AV transit vehicles operating in entrained platoons over portions of the operating “route” with virtual coupling and uncoupling to reach various destinations.
- Deployments in which Supervisory Control Systems manage all AV transit fleet operations in full automation, with human monitoring from the Operations Control Center and with roving operations rapid-response personnel spread throughout the transit network.

7. Findings and Recommendations on AV Technology Deployment in Transit Service

AV technology will impact the public transit industry in a dramatic way during the next two to three decades. Transit Service Types (fixed route, demand-response, etc.) will be the key determinant of the Business Models by which transit services will be delivered. AGT/APM maturation over the last 50 years has shown that design of transit systems with automated functions must be applied in an integrated fashion across multiple subsystems (e.g., vehicle driving, vehicle location determination and guidance, vehicle/station berth interface, V2V and V2I communications, etc.). Thus, a comprehensive safety analysis is needed to adequately mitigate all possible hazardous conditions. Lessons learned from AGT/APM evolution to full automation provide insight into large-scale project implementation, including:

- Enthusiasm about automation can outpace technology maturation.
- R&D of new technology requires major capital investments.
- Partnerships are required across many firms involved with AV transit technology development, civil/architectural design firms, control and communication system integrators, and construction companies, as well as financial firms for some projects.
- Hurdles to deployment typically include funding constraints on supply sources, labor agreements, financial risk sharing, acceptance of full automation, and challenges of accomplishing a safe system design (including ADA compliance).

Enabling AV transit technology is by its nature a complex system but is maturing rapidly. Technology is not expected to be the limiting factor for transit applications, unless the safety requirements are made so stringent that systems are too costly or too complicated to deploy. Specific designs for large transit vehicles combined with progressive demonstration in test environments will likely be the path towards improving safety and mobility of transit operations through automation. This progression of technology capabilities will follow, in general operating environments, the progressive NHTSA/SAE levels of automation. Early deployments of L3 and L4 automation will occur in controlled environments at low speed with limited capabilities of vehicle location determination and vehicle guidance.

Timelines expected for AV transit technology readiness are:

- Near-term (5-10 years) will see applications of AV transit technology to BRT transitways and HOV lanes, in addition to more advanced technology applications for L4 vehicle location determination, guidance and pathing in controlled environments such as campuses.
- Medium-term (10-15 years) will reach L4 driverless vehicle operations in HOV,BRT and low speed mixed traffic environments.
- Long-term (15-30+ years) will have AV transit vehicles operating in all environments and will be integrated into fully automated transit systems.

Subsequent working papers explore in more detail the issues and barriers to adoption of AV transit technology by transit operating agencies. These considerations will frame the roadmap of activities needed to overcome these barriers and improve safety and mobility for transit patrons through automation.

Recommended Research Projects on AV Technology Deployment in Transit Service – The timeline for initial deployment of AV technology in transit service starts now, and the early years of partial automation will be as important as the later years of full automation. The following key research projects are recommended for undertaking based on the considerations and findings of this working paper:

1) ***AV Transit Liability, Insurance and Risk Acceptance*** – Research should be performed into the liability aspects and insurance coverage that will be distributed between the vehicle manufacturer, the operating agency and the human operator, particularly for times when transitions from automated vehicle control to human operator control is a frequent occurrence. The area of focus should be from legal and contractual (collective bargaining) considerations. The related aspects of employee and passenger "acceptance of risk" when onboard public transit vehicle where the human operator is no longer responsible for all functions required to operate the vehicle is a related area also needs further legal research, which could be addressed under this project.
2) ***Legal Constraints to Platooning and Virtual Coupling*** – The concept of dynamically reconfiguring a train (platoon) of AV vehicles has relevant application both in the near term and increasingly in the medium and long term. Anti-platooning and close-following laws in several states are critical regulations that need to be addressed in this research project to determine their legal application to buses in BRT transitways or HOV lanes for the near term. And for the long term the legal implications of such laws should be assessed for lower-speed arterial street as well as high-speed freeway operating conditions.
3) **Features and Configurations of Transit Fixed Facilities** – Beginning with an assessment of the practical and technical implications for providing more direct service without intermediate stops using off-line stations, a research project is needed to evaluate the implications for operations in line-haul high-capacity. The work should evaluate how this new concept could potentially allow almost all stations to be designed for fewer number of vehicle berths. Near to medium term changes to transit fixed facilities should be studied in more detail through research activities that explore features and right-of-way requirements for station/stop locations, transition zones from the main operating lanes into off-line stations, and the configuration of multi-berth boarding positions
4) **Virtual Entrainment of AV Transit Vehicles** – Research is needed into the long-term implications of dynamic entrainment with virtual coupling/uncoupling to allow longer "trains" moving through the transitway/roadway system then separating into individual vehicles when berthing at stations.
5) **Station Platform Edge Partitions and Doors** – The safety benefits and costs of adding platform edge partitions and automated doors should be addressed in a research work as a potential feature needed in stations with high levels of passenger activity. Actions by multiple automated metro systems around the world to design for and even retrofit this type of station equipment in fixed guideway transit systems needs to be evaluated considering AV transit technology features and capabilities.

Glossary of Terms and Acronyms

ACC – Adaptive Cruise Control

ADA – Americans with Disabilities Act

ADS – Automated Driving System (SAE defined term)

AGT – automated guideway transit

AHS – Automated Highway System

APM – automated people mover

ATN – automated transit network

ATO – automated train operations

ATP – automated train protection

ATS – automated train supervision

AV – automated roadway vehicle

BRT – bus rapid transit

BIM – basic infrastructure message

BSM – basic safety message

BSW – blind spot warning

CACC – cooperative adaptive cruise control

CBTC – communications based train control

CAMP – Collision Avoidance Metrics Partnership

CV – connected roadway vehicle

CVPD – connected vehicle pilot deployment

DARPA – Defense Advanced Research Projects Agency

DDT – dynamic driving task (SAE defined term)

DGPS – differential global positioning system

DSRC – digital short range communications

FCW – forward collision warning

GID – geographic intersection description

GPS – global positioning system

HERE – a private supplier of real-time traffic data, online maps, embedded navigation tools, and high definition maps for automated driving

HOV – high occupancy vehicle

IMTS – Intelligent Multimodal Transit System, a Toyota brand name

ITS – intelligent transportation systems

LDW – lane departure warning

LiDAR – light detection and ranging

LRT – light rail transit

LTE – long term evolution

NHTSA – National Highway Traffic Safety Administration

OBU – on-board unit

OEM – original equipment manufacturer

OCC – operations control center

ODD – operational design domain (SAE defined term)

OEDR – object and event detection response (SAE defined term)

PATH – Partners for Advanced Transportation Technology; Caltrans PATHPRT – personal rapid transit

RSU – roadside unit

SAE – Society of Automotive Engineers

SPaT – signal phase and timing

SRM – signal request message

SSM – signal service message

TSP – transit signal priority

USDOT – United States Department of Transportation

V2I – vehicle-to-infrastructure communications

V2V – vehicle-to-vehicle communications

V2X – vehicle-to-other road users

VAA – Vehicle Assist and Automation

References

Aoki, Keiji and Rie Hayashida; *(2005); "A New Public Transport System that Bridges the Gap between Cars and Rail: 'IMTS' ";* ASCE 10th International Conference on Automated People Movers, May 2005.

ASCE 21-13, Automated People Mover Standards, American Society of Civil Engineers, 2013.

IEC 62267 Railway Applications, Automated urban guided transport (AUGT) – Safety Requirements, Edition 1.0 2009-07, International Electrotechnical Commission, 2007.

Lott, J. Sam and Eugene Nishinaga; (2005); *"Optimizing AGT Applications Through Demand-Responsive Control Systems"*; ASCE 10th International Conference on Automated People Movers, May 2005.

Lott, J. Sam and David S. Tai; (2005); *"Capacity Analysis of Demand Responsive Transit Systems"*, Transportation Research Board; TRB Annual Conference, January 2005.

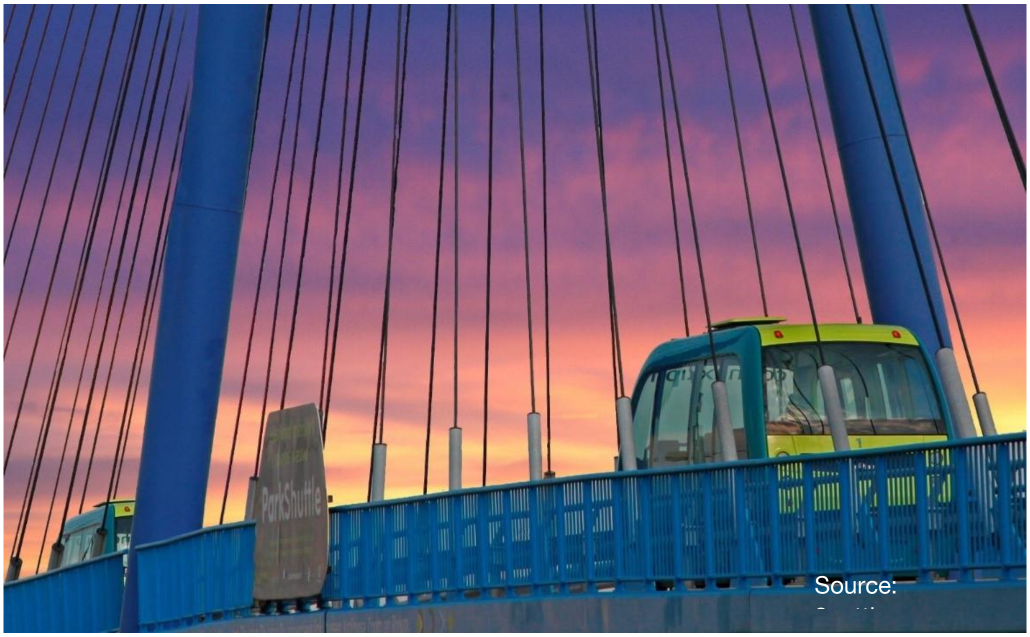
Lott, J. Sam, Douglas Gettman, Ph.D. and David S. Tai; (2009); *"Simulation Analysis of APM Systems in Dense Urban Environments – Part 1: Transit User Experience and Part 2 System Operations"*; ASCE 12th International Conference on Automated People Movers, June 2009.

Appendix A
Automated Vehicle System Technologies Designed to Comply with ADA Requirements

Rivium Park Shuttle, Capelle, Netherlands

This fully automated bus system is in the Rivium Office Park and designed by 2getthere, a company based in the Netherlands. The current vehicle technology was installed in 2005 and operates along a dedicated transitway with station boarding locations providing docking at each vehicle berth. The vehicles operate with “free-ranging” vehicle location determination within the transitway using magnetic markers placed on specific intervals in the running surface.

Source:



Rivium Park Shuttle Protected Station Platform

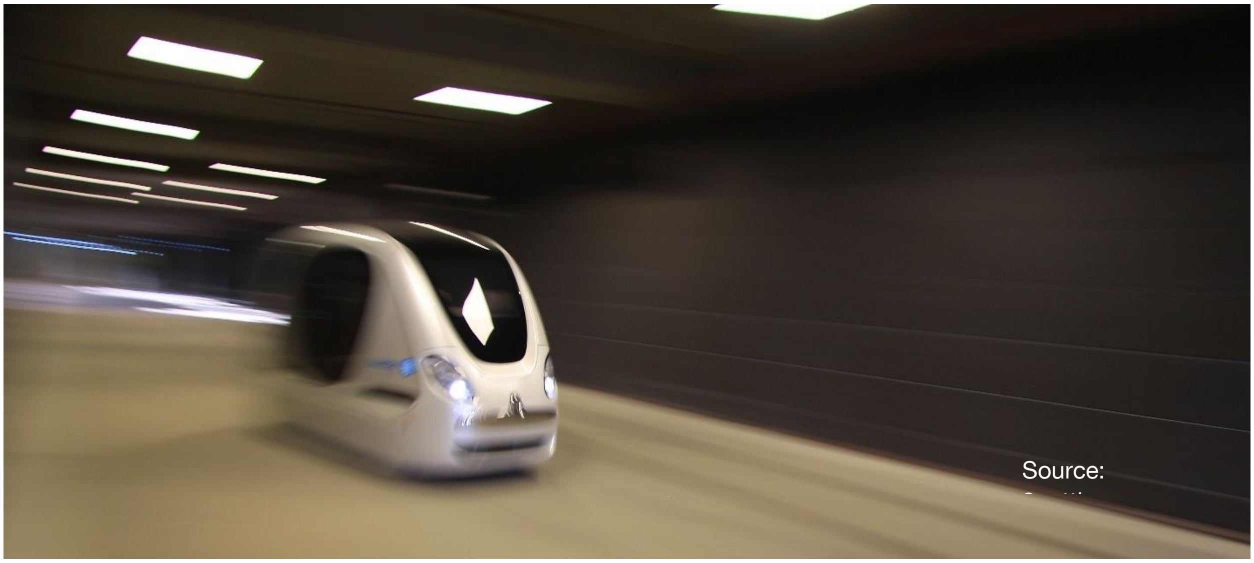
2getthere now has announced an updated GRT vehicle design that is shown below in the images provided by 2getthere. For additional information, refer to the company website: www.2getthere.eu

Newest GRT Vehicle Design by 2getthere Automated Transit System Supplier

Masdar City PRT System, Abu Dhabi

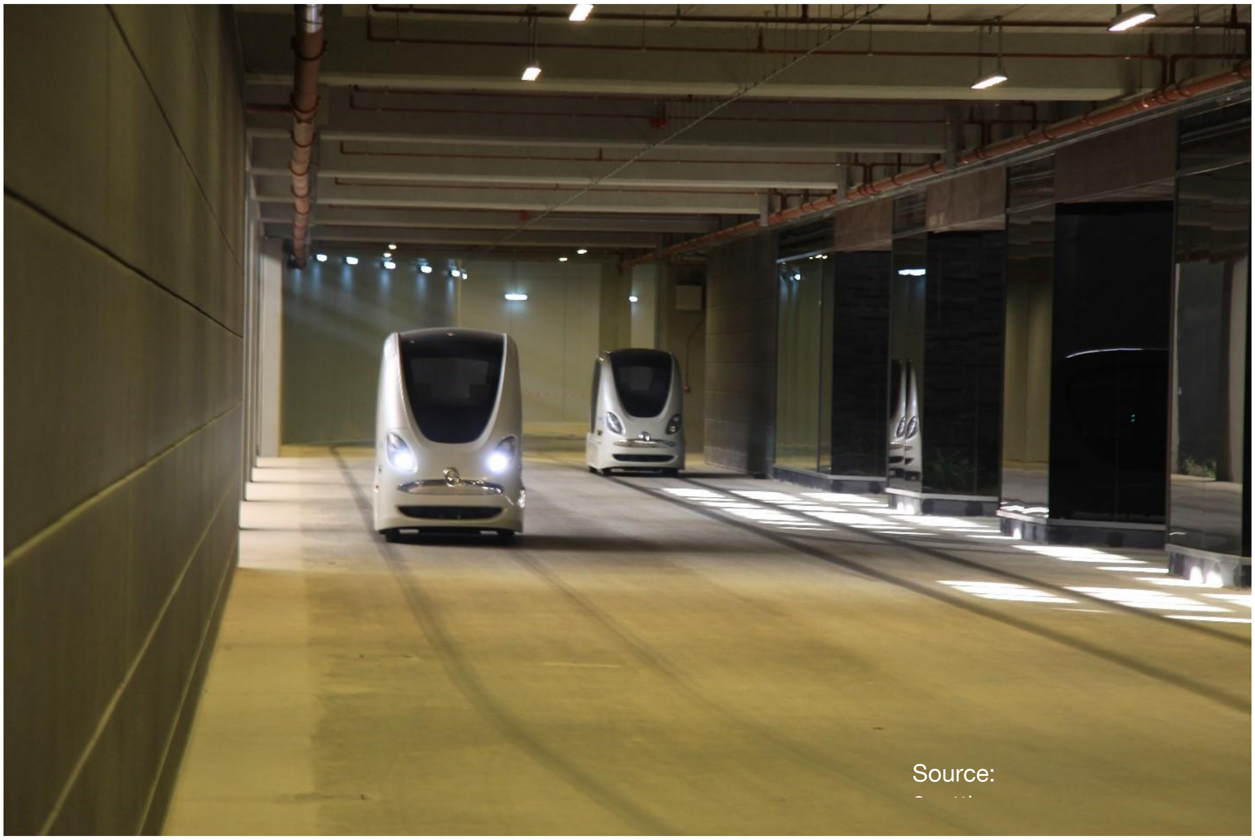
The PRT system designed, installed and operated by 2getthere began service in 2010, and an expansion of the Masdar City development has just been announced in April 2016. The small vehicle system will seat 4 adults and provides direct origin to destination service. The vehicles enter station berths that have full platform edge protection, and after the station dwell the vehicles back out of the berth to resume their travel through the transitway. The Masdar City system operate below the buildings above, in part to protect the operating environment from the severe heat of the Abu Dhabi desert climate.

The vehicles are fully-automated robotic vehicles, steering themselves and tracking their location from magnetic markers that are embedded in the running surface. The precision of the travel path is so accurate that the tires of successive vehicles follow exactly along the same tire contact areas as the vehicles before.


Source:


Source:


Source:



The 2getthere website reports that the system availability and vehicle reliability consistently exceed 99.4% and 99.8%, respectively. The Phase 1A system encompasses 5 stations – 2 for passenger vehicles and 3 for freight vehicles. 10 passenger vehicles and 3 freight vehicles have been in service throughout the life of the system, and on May 22nd 2014 at 13.55 hours, the system carried its 1 millionth passenger.

Deployment of the company's original automated vehicle technology began in in the 1990s with a container handling system at the Rotterdam Seaport that utilized the magnetic marker location system for robot transportation location in a configuration called the FROG system (free ranging on grid). Since that time there have been multiple passenger and freight carrying systems that represent progressive design development.

Heathrow ULTra PRT System

Source: ULTra

The ULTra PRT System technology was successfully deployed at Heathrow International Airport connecting Terminal 5 with a remote long term parking facility and has operated for over five years. The details of the vehicle design were developed over a number years from the original vision and design innovation of the late Dr. Martin Lowson, a well-known aerospace research engineer and university professor.

Testing and development work were performed at a test track near Bristol, England for several years prior to the Heathrow deployment. The Houston Airport System was interested in the ULTra vehicle system technology during a series of studies to assess options to replace the Bush Intercontinental Airport tunnel train system, and a delegation of HAS and Continental Airline representatives traveled to the ULTra test track in 2004. Photographs taken during visits to the ULTra test track are shown below.

Known to many as the Heathrow Pod System, the airport automated transit network system uses “robotic” vehicles that steer them-selves along a transitway comprising two concrete pads for tire running surfaces and side curbs by which the vehicle detects its position using laser technology. ULTra vehicles have carried 700,000 Heathrow passengers since 2011, and average about 800 passengers a day traveling between the three stations in what is designated the Phase 1A system.

An operating fleet of 21 vehicles travels over 3.8 kilometers (approximately 2.5 miles) of one-way guideway, connecting Terminal 5 with a remote parking facility. The flexibility of the small vehicle technology allowed it to be retrofitted into the terminal landside design after the other roadway and parking infrastructure was already under construction, as shown in the photo below. Plans have been developed to ultimately extend the ULTra system into the central terminal area.

The ULTra PRT technology was first installed at the London Heathrow International Airport and passenger service began in 2011. During the process of the contractual agreements for this deployment, BAA – the owner of Heathrow Airport – became an equity owner with ATS ULTra of the technology. The company now goes under the name of ULTra Global PRT – see the company website at: www.ultraglobalprt.com

ULTra PRT Test Track Photos (2004 – 2008)

Source: ULTra

Source: Kimley-Horn

ULTra guideway system was retrofit into the Heathrow Airport Terminal 5 roadway and parking infrastructure after it was already under construction

Source: ULTra

Source: ULTra

Source: ULTra

Appendix B
Summary of Implications/Interpretation of SAE J3016 Taxonomy and Definitions for AV Public Transit Applications

The Society of Automotive Engineers has issued an updated version of SAE J3016[37] (copyrighted) as a Recommended Practice standard on September 30, 2016 and is titled "Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles". This standard provides a consensus within the automotive industry on definitions, nomenclature and terms for "automate driving systems", including a taxonomy (system of classification) of the different level of driving automation. Simultaneously in September 2016, the National Highway Traffic Safety Administration release the official USDOT policy statement regarding the official "Federal Automated Vehicle Policy." The NHTSA policy statement has now officially adopted the SAE J4016 taxonomy defining the levels of driving automation – Levels 0-5.

The information contained in this appendix is intended to provide insight into the SAE definitions and taxonomy from the perspective of applying automated vehicle (AV) technology to public transit system operations. As such, this is an interpretive discussion and is not representative of the opinions or intent of the Society of Automotive Engineers or the US Department of Transportation.

The introduction to the standard provides the following explanation of its purposes:

- Clarifying the role of the (human) driver, if any, during driving automation system engagement.
- Answering questions of scope when ti comes to the developing laws, policies, regulations, and standards.
- Providing a useful framework for driving automation specifications and technical requirements
- Providing clarity and stability in communications on the topic of driving automation, as well as a useful short-hand that saves considerable time and effort.

Scope

The statement of scope clearly distinguishes between the driving tasks which may be automated, and the other systems and features of the vehicle, such as active safety systems like stability control and automated emergency braking. The standard only deals with driving automation systems/functions, and not the many other functional components and systems of a roadway vehicle. It does, however, address the interactions of the driving automation systems with humans, and with human drivers.

The nature of other systems and features of the vehicle, such as active safety systems like stability control, lane departure alerts and automated emergency braking which are "momentary" in their applications mentioned, but they are considered different from the task of "driving" as defined by SAE J3016. These "other" vehicle systems are certainly applicable to

[37] SAE J3016™ SEP2016, Superseding J3016 JAN2014

aspects of AV transit applications, whether the human driver is engaged in the driving process. But regarding the SAE J3016 standard, they are not included since it is a "driving automation" standard.

Roles and Responsibilities of Automated Driving Actors

The document identifies three "primary actors" that are inherently involved in the driving process – the (human) driver, the driving automation system, and other vehicle systems and components such as those mentioned above. Even if hardware and software is shared between the other vehicle systems and the driving automation system, they are considered distinct in their role. This is a very important and intentional limitation of the SAE J3016 standard.

The actual driving process is defined as the Dynamic Driving Task (DDT) which is performed in a sustained manner. The levels of driving automation are defined with respect to the specific "role" played by the primary actors within the DDT.

Table 4 is an excerpt from the J3016 document, which illustrates the roles and responsibilities of each actor for each level of automated driving. Other important functional definitions and associated acronyms that are included in **Table 4** are:

Automated Driving System (ADS) – defined by SAE for L3, L4 and L5 levels of driving automation have also been adopted by NHTSA[38]. Note that SAE emphasizes that a "driving automation system" refers to features that may be used in lower levels of L1 and L2 driving as well as L3-L5 driving automation, whereas only ADS features/capabilities apply to L3, L4 and L5.

Dynamic Driving Task (DDT) – Refers to the real-time functions that are both operational and tactical and necessary to operate a vehicle in traffic, but not strategic decisions of trip planning and scheduling.

Operating Design Domain (ODD) – The specific boundary conditions within which a given ADS or driving automation feature is designed to function, including geographic, roadway, environmental, traffic, speed, and/or temporal limitations. ODD applies to L1, L2, L3 and L4 levels of automation, but not L5.

Dynamic Driving Task Fallback – The DDT Fallback is the condition of "minimum risk" condition when either the ADS vehicle experiences a DDT "performance-relevant system failure" or upon ODD exit.

DDT Fallback-Ready User – This definition applies specifically to a L3 level of automation where the ADS may need to hand-back the driving task upon short notice, and the "user" who is alert and monitoring the ADS operations such that they are "receptive" to intervene and take control of the vehicle.

Minimal Risk Condition – Defined as a condition where an ADS may execute a DDT Fallback to reduce the risk of a crash when the assigned trip cannot or should not be completed. For L4 or L5 levels of driving automation, the necessary minimal risk condition may be reached by a

[38] NHTSA/USDOT defines a Highly Automated Vehicle (HAV) as having an L3, L4 or L5 level of driving automation.

DDT Fallback when a performance-relevant system failure occurs or when the vehicle exits the vehicle's specific ODD. The minimal risk condition may involve the vehicle automatically:

- Bringing itself to a stop within its current travel path;
- Performing a maneuver to take the vehicle from the active traffic lane and then bring itself to a stop; or
- Return the vehicle to its dispatching facility.

Table 4. SAE J3016 Roles of Human Driver and Driving Automation System by Level of Driving Automation– Source: Society of Automotive Engineers (Page 1 of 3)

Level of *Driving Automation*	**Role of *User***	**Role of *Driving Automation System***
DRIVER* PERFORMS THE *DYNAMIC DRIVING TASK (DDT)		
Level 0 - *No Driving Automation*	*Driver* (at all times): • Performs the entire *DDT*	*Driving Automation System* (if any): • Does not perform any part of the *DDT* on a *sustained* basis (although other *vehicle* systems may provide warnings or support, such as momentary emergency intervention)
Level 1 - *Driver Assistance*	*Driver* (at all times): • Performs the remainder of the *DDT* not performed by the *driving automation system* • *Supervises* the *driving automation system* and intervenes as necessary to maintain safe *operation* of the *vehicle* • Determines whether/when engagement or disengagement of the *driving automation system* is appropriate • Immediately performs the entire *DDT* whenever required or desired	*Driving Automation System* (while engaged): • Performs part of the DDT by executing either the *longitudinal or* the *lateral vehicle motion control* subtask • Disengages immediately upon *driver* request
Level 2 - *Partial Driving Automation*	*Driver* (at all times): • Performs the remainder of the *DDT* not performed by the *driving automation system* • *Supervises* the *driving automation system* and intervenes as necessary to maintain safe *operation* of the *vehicle* • Determines whether/when engagement and disengagement of the *driving automation system* is appropriate • Immediately performs the entire *DDT* whenever required or desired	*Driving Automation System* (while engaged): • Performs part of the *DDT* by executing both the *lateral and* the *longitudinal vehicle motion control* subtasks • Disengages immediately upon *driver* request

Table 4. SAE J3016 Roles of Human Driver and Driving Automation System by Level of Driving Automation – Source: Society of Automotive Engineers (Page 2 of 3)

AUTOMATED DRIVING SYSTEM (ADS) **PERFORMS THE ENTIRE** ***DYNAMIC DRIVING TASK (DDT)***		
Level 3 – *Conditional Driving Automation*	*Driver* (while the ADS is not engaged): • Verifies operational readiness of the *ADS-equipped vehicle* • Determines when engagement of *ADS* is appropriate • Becomes the *DDT fallback-ready user* when the *ADS* is engaged *DDT fallback-ready user* (while the *ADS* is engaged): • Is *receptive* to a *request to intervene* and responds by performing *DDT fallback* in a timely manner • Is *receptive* to *DDT performance-relevant system failures* in *vehicle* systems and, upon occurrence, performs *DDT fallback* in a timely manner • Determines whether and how to achieve a *minimal risk condition* • Becomes the *driver* upon requesting disengagement of the *ADS*	*ADS* (while not engaged): • Permits engagement only within its *ODD* *ADS* (while engaged): • Performs the entire *DDT* • Determines whether *ODD* limits are about to be exceeded and, if so, issues a timely *request to intervene* to the *DDT fallback-ready user* • Determines whether there is a *DDT performance-relevant system failure* of the *ADS* and, if so, issues a timely *request to intervene* to the *DDT fallback-ready user* • Disengages an appropriate time after issuing a *request to intervene* • Disengages immediately upon *driver* request

Level 4 - High Driving Automation	*Driver/dispatcher* (while the *ADS* is not engaged):
	• Verifies operational readiness of the *ADS-equipped vehicle*
	• Determines whether to engage the *ADS*
	• Becomes a *passenger* when the *ADS* is engaged only if physically present in the *vehicle*
	
	Passenger/dispatcher (while the *ADS* is engaged):
	• Need not perform the *DDT* or *DDT fallback*
	• Need not determine whether and how to achieve a *minimal risk condition*
		ADS (while not engaged):
		• Permits engagement only within its *ODD*
		
		ADS (while engaged):
		• Performs the entire *DDT*
		• May issue a timely *request to intervene*
		• Performs *DDT fallback* and transitions automatically to a *minimal risk condition* when:
		  ◦ A *DDT performance-relevant system failure* occurs or
		  ◦ A *user* does not respond to a *request to intervene* or

Table 4. SAE J3016 Roles of Human Driver and Driving Automation System by Level of Driving Automation – Source: Society of Automotive Engineers (Page 3 of 3)

	• May perform the *DDT fallback* following a *request to intervene* • May request that the *ADS* disengage and may achieve a *minimal risk condition* after it is disengaged • May become the *driver* after a requested disengagement	• A *user* requests that it achieve a *minimal risk condition* • Disengages, if appropriate, only after: • It achieves a *minimal risk condition* or • A *driver* is performing the *DDT* • May delay *user*-requested disengagement
Level 5 - Full Driving Automation	*Driver/dispatcher* (while the *ADS* is not engaged): • Verifies operational readiness of the *ADS*-equipped vehicle • Determines whether to engage the *ADS* • Becomes a *passenger* when the *ADS* is engaged only if physically present in the *vehicle* *Passenger/dispatcher* (while the *ADS* is engaged): • Need not perform the *DDT* or *DDT fallback* • Need not determine whether and how to achieve a *minimal risk condition* • May perform the *DDT fallback* following a *request to intervene* • May request that the ADS disengage and may achieve a *minimal risk condition* after it is disengaged • May become the *driver* after a requested disengagement	*ADS* (while not engaged): • Permits *engagement* of the *ADS* under all driver-manageable on-road conditions *ADS* (while engaged): • Performs the entire *DDT* • Performs *DDT fallback* and transitions automatically to a *minimal risk condition* when: • A *DDT performance-relevant system failure* occurs or • A *user* does not respond to a *request to intervene or* • A *user* requests that it achieve a *minimal risk condition* • Disengages, if appropriate, only after: • It achieves a *minimal risk condition* or • A *driver* is performing the *DDT* • May delay a *user*-requested disengagement

DDT Performance-Relevant System Failure – Malfunction which causes either the driving automation system or the other vehicle systems to fail and prevent the Automated Driving System of an L3, L4 or L5 level of driving automation from performance the DDT per design intention.

Within the terminology there are three different modes of human interaction with the AV transit vehicle as a "user" riding inside the vehicle – a passenger, a driver, and a DDT fallback-ready user (e.g., a transit system employee that is trained, alert and prepared to assume the dynamic driving task when the vehicle terminates its automated operations mode). In addition, there is a defined role for persons who are "remote users" not inside the vehicle – remoted driver, DDT fallback-ready user, or a dispatcher.

Exiting the Dynamic Driving Task Under Automated Driving of L4 or L5

Table 5 excerpted from SAE J3016 shows these possible roles that users, drivers and dispatchers may play for the different levels of driving automation.

Table 5. User's Roles When a Automated Driving System is Engaged
Source: Society of Automotive Engineers

	No *Driving* Automation	Engaged Level of *Driving Automation*				
	0	1	2	3	4	5
In-*vehicle User*	*Driver*			*DDT fallback-ready user*	*Passenger*	
Remote *User*	*Remote Driver*			*DDT fallback-ready user*	*Dispatcher*	

SAE J3016 provides a specific notation below the table shown in **Table 5** which provide substantial insight into the way that transit applications of AV technology will require a continued monitoring, supervision and intervention/action on the part of operations personnel. And as specifically described in the example, even when the system achieves its capability to operate in public transit service without requiring an employee to be onboard (L4 and L5) there will be certain applications that will require a human operator to take control of the vehicle at certain locations and times. The parenthetical definitions of acronyms have been added for ease of reading.

- NOTE (ref. **Table 5** above): "A vehicle equipped with a level 4 or 5 ADS (Automated Driving System) may also support a driver role. For example, to complete a given trip, a user of a vehicle equipped with a level 4 ADS feature designed to operate the vehicle during high-speed freeway conditions will generally choose to perform the DDT (Dynamic Driving Task) when the freeway ends; otherwise the ADS will automatically perform DDT Fallback and achieve a minimal risk condition as needed. However, unlike at level 3, this user is not a DDT fallback-ready user while the ADS is engaged."

This Note for **Table 5** specifically describes how in this example an AV public transit vehicle will operate when:

1. L4 automation is bounded by geo-fencing and/or roadway classification;
2. A transition to a human operator to assume the driving task must occur at the transition point from the boundary location; and
3. If no operator is ready to assume the “dynamic driver task” in a timely manner, the vehicle will initiate a “fallback” mode to bring it to a stop in a pre-defined “minimum risk” condition and location.

Finally, the standard defines an ADS Dedicated Vehicle (ADS-DV) as a vehicle designed to be operated exclusively for L4 operations within a specific ODD, or a vehicle designed for L5 that is capable of operating on all roads navigable by a human driver. These are vehicles capable of operating without any person onboard who is qualified to be a driver or operator, and these vehicles may or may not have typical driving interfaces such as brakes, steering, gear-selection input devices. But the vehicles will be able to be operated by a driver who accesses the vehicle or by a dispatcher/remote-operator who can take control of the vehicle to drive it from the operational “fallback” stop location.