NREL

The Automated Mobility District Implementation Catalog, 2nd Edition

Safe and Efficient Automated Vehicle Fleet Operations for Public Mobility

Part 1: Progress of Automated Vehicle R&D for Deployments in Passenger Service
Part 2: 10 Early Deployment Sites as Prototypes of AMD Implementation
Part 3: Five Cardinal Principles for AMD Implementation

Stanley Young[1] and J. Sam Lott[2]

1 National Renewable Energy Laboratory
2 Automated Mobility Services, LLC

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Foreword

This second edition in the *Automated Mobility District Implementation Catalog* series has been prepared by the National Renewable Energy Laboratory (NREL) for the benefit of early adopters, researchers, and their associated stakeholder community pursuing early deployments of automated vehicle (AV) technology for public mobility, often referred to "AV shuttles." The second edition of this catalog series, like the first, is intended to inform stakeholders considering automated mobility district (AMD) implementations by conveying a history of significant deployments and demonstrations and their related findings and lessons learned. Through this body of information, the intent is that new endeavors can benefit from the collective experience of others. This edition complements and extends the first edition available at no charge from https://www.nrel.gov/docs/fy20osti/76551.pdf.

In addition to the continuation of 10 early-stage comparative "site deployment" summaries to inform of insights and lessons learned, this edition begins to draw overall system-level commonalities leading to substantial emphasis on the need for an AMD jurisdictional authority and complementary intelligent roadway infrastructure (IRI). IRI, combined with appropriate system-level safety integration, is required not only for the safety of automated vehicle deployment, but also to ensure equitable distribution of benefits to all roadway users, both automated and non-automated, as well as vehicles, transit, and non-motorized users such as pedestrians, cyclists, and other micromobility users. Equally important is the sustainability benefit of energy management and efficiency of operations that IRI can produce.

As opportunity and funding allow, NREL plans to keep this *Automated Mobility District Implementation Catalog* series up to date and relevant as projects and demonstrations come online and reach sufficient maturity to produce appropriate insight and lessons learned. As a "living document" that will be continually improved and advanced, the submittal of additions and corrections to information in this catalog is welcomed and encouraged.

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Preface

The first edition of the *Automated Mobility District Implementation Catalog* was published by the NREL to document insights gained from monitoring 10 early deployment sites of AV technology. The 10 sites spanned settings as diverse as urban districts, sports complexes, university campuses, and master planned residential communities. When published in 2020, the first edition compiled the lessons learned from the initial phase of pilot programs, given primarily from the view of the sponsoring public agencies, with further insight included from the perspectives of the operating companies and the AV technology developers.

Since the publishing of the first edition 2 years ago, our tracking of the effects the 2020 pandemic and the progress of the demonstration pilot projects beyond the initial deployment phase has generated important new information. The objective of this second edition is to provide an update to the status of the 10 early deployment sites in order to assess common trends of technology development and deployment. Drawing from that new insight, the objective is to document the natural maturing of the AV technology industry. Most importantly to NREL, this second edition reports on the framework of "cardinal principles" that the research team has defined for the safest and most efficient application of AV technology in managed fleet deployment within automated mobility districts of the future.

This second edition of the *AMD Implementation Catalog* series has been prepared in three parts to assist readers in their review and understanding of the technical information herein. The material may be more easily ingested if each of the three parts is read and then contemplated for its ramifications to the specific interest of the reader before continuing to the next part. Further, each part has been prepared with the intent that it could be read independently from the others.

Part 1: Progress of Automated Vehicle R&D for Deployments in Passenger Service

> Part 1 comprises Sections 1 and 2 that address what has occurred in the development of AV technology, based to a large extent on the observations and assessments of the 10 early deployment sites documented in the first edition. This collection of R&D data is drawn from these AV technology applications within specific districts in which public mobility through use of AV technology has been implemented within specific and limited geographical boundaries. Other trends of development for passenger transport in urban districts are also considered in the view of the industry status.

Part 2: 10 Early Deployment Sites as Prototypes of AMD Implementation

> The 10 sites originally described in the first edition have updated articles included as subsections of Section 3. Each article reports information obtained from the owner/sponsoring agency that is responsible for initiating the site AV deployment. Some sites have brief descriptions of other AV deployments now underway, which are spinoffs from the original AV deployment in that respective city.

Part 3: Five Cardinal Principles for AMD Implementation

> Drawing from the information on the status of the industry overall and the specific 10 deployment sites, Part 3 presents the authors' conclusions on the primary lessons learned and the overall principles to be applied with regard to the near- to medium-term implementation of automated mobility districts. The discussion is progressively developed through Sections 4, 5, and 6, with a final statement of conclusions presented in Section 7.

As supporting information to the content of this written document, a series of presentation videos has been prepared to provide further discussion of the content in Part 3. These presentations are based on technical papers by the authors that were published as part of conference proceedings during 2021. These NREL presentations are based on three conference presentations given during 2021, as noted in Appendix B.

Appendix B contains the abstracts for the presentation videos, as well as the citations for the two associated technical papers. Quick links that provide online access the NREL presentations and the published papers are embedded in the appendix text.

Finally, note that the written information herein was current as of April 2022, and project changes and new information that may have been released by the identified deployment sites after that point in time have not been included in this document.

Acknowledgments

The authors would like to acknowledge the contributions from our many collaborators, particularly from the 10 early-stage AMD deployments for sharing data and lessons learned and carefully reviewing the summary of their respective deployments. The authors would also like to thank and acknowledge external reviewers for their thorough review of the manuscript: Tom Bamonte, Senior Program Manager for Automated Vehicle Technology from the North Central Texas Council of Governments, and Dr. Lei Zhu, Assistant Professor at the University of North Carolina, Charlotte, and Director of the Smart Infrastructure and Mobility Systems Laboratory within the Engineering and Engineering Management Department.

List of Acronyms

ADA	Americans with Disabilities Act
ADS	automated driving systems
AMD	automated mobility district
AV	automated vehicle
BRT	bus rapid transit
BSIC	Bay Street Innovation Corridor
CDA	cooperative driving automation
DDT	dynamic driving task
FMVSS	Federal Motor Vehicle Safety Standards
FTA	Federal Transit Administration
IRI	intelligent roadway infrastructure
JTA	Jacksonville Transportation Authority
LRT	light rail transit
mph	miles per hour
NHTSA	National Highway Traffic Safety Administration
NREL	National Renewable Energy Laboratory
ODD	operational design domain
RFP	request for proposals
RTC	Regional Transportation Commission of Southern Nevada
RTD	Regional Transportation District
TSU	Texas Southern University
U of H	University of Houston
U^2C	Ultimate Urban Circulator

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- **What we have learned from 10 early AV pilot projects**
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- **Findings and observations from AV development**

1 Introduction: Formative AMD Parameters

The evolution of automated vehicle (AV) technology is making steady progress. The anticipated timelines for unmanned, self-driving cars and buses transporting passengers throughout our major urban areas have passed the dates of the earliest estimates of their deployment in fully automated operation. In fact, promised future dates for fully unattended Level 4 operations[1] in mixed-traffic conditions are now being offered more cautiously by the developers of AV technology, and if dates are given, it is usually for a few selected applications with well-defined operational design domains (ODDs).

This new reality for what in popular vernacular is often called "autonomous" vehicles is that the final stages of development are much more difficult than first believed. This is not a flaw of the R&D initiatives, but rather simply a case of having the great anticipation of the benefits of AV technology driving unrealistic timelines that created premature expectations.

This second edition of the *Automated Mobility District Implementation Catalog* explores what progress has been made over the past 2 years, with its content current through April 2022. It assesses the path forward for achieving meaningful automated mobility solutions and—based on these assessments—proposes where and how the most beneficial concentrations of AV deployment should be realized over the coming decade.

In achieving this perspective on the path forward, the path already traveled will be kept in focus. Specifically, the important frame of reference formed by the 10 early deployment sites documented in the first edition of this series will provide a grounded perspective on how fast progress is being made toward the vision of a fully automated mobility future.

1.1 AMD Concept for 2025 Implementation

The concept of an automated mobility district (AMD) was developed by the Mobility Innovations and Equity Team at the National Renewable Energy Laboratory (NREL) to explore energy use and efficiencies that appear to be possible within dense urban areas. The first edition of the *AMD Implementation Catalog* series[2] introduced the concept in the following way:

> "An Automated Mobility District is a geographically confined district or campus-sized implementation of connected and automated vehicle technology for the purpose of publicly accessible mobility by which all the potential benefits of a fully automated mobility services can be realized."

Based on the progress of the last 5 years of AV development and a number of demonstration pilots, it is clear that a fully functional AMD can be realized by 2030 in a number of locations, with early versions of the AMD concepts certain to be demonstrated as early as 2025. It is becoming equally clear that the path forward to accomplish this goal on a large scale will require new perspectives on what constitutes the AV "system" providing these services when it

[1] SAE International has defined a hierarchy of levels of automation, with Level 4 representing "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." Table 1 - Summary of levels of driving automation, pg. 17, J3016 SEP2016.
[2] Young, Stanley and J. Sam Lott. 2020. *The Automated Mobility District Implementation Catalog: Insights from Ten Early-Stage Deployments*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5400-76551. https://www.nrel.gov/docs/fy20osti/76551.pdf.

encompasses the whole spectrum of ride-hailing, transit, and package delivery services—something that is discussed in Part 3 as a "system-of-systems."

This system-level view is the focus of this second edition in the *AMD Implementation Catalog* series, and the sections that follow investigate not only the evolution of the vehicle technology, but also the necessary deployment of vehicle fleet management systems and the management of the multimodal transportation infrastructure of the AMD within which the AV fleets operate. The role of the AMD management authority is explored, and its jurisdictional responsibilities are described in a preliminary form. The full evolution of this new entity as the "authority having jurisdiction" for safe and efficient AV operations in dense urban environments will no doubt be one that the whole industry participates in creating and shaping, but the early concepts are taking shape now, and these form the path forward—as described in the following sections.

Further, the systems view of the operating environment must also address the safety and protection of the other roadway users that will move along the urban street system. These important roadway users establish the full multimodal context of the operations that the AMD management authority must oversee. The "mixed-traffic" operating environment is actually a major driving force to expanding the view and understanding of the "automated mobility system" environment discussed in the sections that follow. In particular, the reality is discussed in which non-automated vehicles operated by humans, as well as pedestrians and other active forms of human transportation like bicycles and electric scooters, will continue to be a significant and vital part of the overall traffic mix.

And finally with respect to the emphasis on the "dense urban environment" for which the AMD concept is proposed, the following consideration is offered. Although no strict parameters on density are provided, 'sufficient density' implies that demand is sufficient to justify automated AV fleet operations. The justification could be viewed such that if access is limited to only personal vehicles, then as a result the parking requirements would exceed available supply. Another aspect of density could be viewed as having person-trip demand patterns such that traditional transit shuttle services are inefficient to distribute the demand. Future editions of the AMD catalog will attempt to place measurable parameters on the meaning of a "dense urban environment" suitable to justify AMD implementation.

1.2 Recent Changes in the AV Industry and Petitions to NHTSA

Over the 2 years since the first edition of the *AMD Implementation Catalog* was published, the AV industry has seen several mergers, acquisitions, or "acqui-hires" of all the employees of one AV technology company by another technology company. Equally significant is the major investor capitalization and assumption of controlling interest in several startup companies involved in R&D work for automated driving systems (ADS). Some firms have been acquired and absorbed into larger companies, with vehicle original equipment manufacturers selecting which ADS startup they will buy for their positioning to eventually deploy Level 4 ADS within their product lines, and to bolster their work in the progressive rollout of Level 1 through Level 3 automated driving assistance technology.

There have also been some ADS startup firms, or associated firms developing AV shuttle vehicle platforms, that have simply gone out of business—some within the first few months of 2022 that preceded the publication of this document. This contraction in the AV shuttle field of players has been driven in part by the realignment of the business plan for some startup ADS developers in order to focus on the freight and cargo market for their AV technology deployments. As a result of these industry transformations, some firms have announced their departure from the AV field of actively pursuing the passenger transport marketplace.

Examples of these types of changes are referenced throughout the discussion of the 10 early deployment sites found in Part 2. These 10 sites were chosen for tracking of their progress over the last 5 years specifically for the purpose of studying these trends.

But even as the number of companies actively working in the field commonly referred to as "AV shuttles" is contracting and consolidating, there have been notable new entries to this field by several major companies that have bought controlling interest of small startup ADS developers. These entities have shuttle vehicle designs that are being readied for mass production as the market matures—notably Cruise (GM), Zoox (Amazon), and 2getthere (ZF). Cruise[3] and Zoox[4] are well known from the AV press coverage they receive, but the 2getthere[5] AV shuttle technology is still emerging in its recognition here in the United States.

The European roots of 2getthere and their new owner ZF form a powerful combination that is committed to delivering automated mobility systems to the public transport market in North America. 2getthere is an ADS and AV shuttle vehicle design company based in the Netherlands, and Section 3.7 describes the current status of the system they originally deployed 20 years ago in the Rivium Business Park near Rotterdam. Equally important is the fact that ZF is one of the world's largest component and subassembly suppliers to the original equipment manufacturer automobile industry.

The entry of these major companies into the field of AV shuttles has resulted in the National Highway Traffic Safety Administration (NHTSA) acknowledging that this class of AV designs has no provisions for traditional human drivers within the interior of the passenger cabin. After specific petition from General Motors [6], the parent company of Cruise, NHTSA is giving initial indications that certain vehicles designed for driverless operation will be considered for special exemptions from some aspects of the Federal Motor Vehicle Safety Standards (FMVSS). This was granted in light of there being no need for things like a steering wheel or brake pedal.

Although NHTSA has yet to issue comprehensive rules for AV deployment overall, the provision of current law that an exemption from FMVSS can be given for up to 2,500 vehicles could be the basis for NHTSA to allow the initial AV shuttle deployments for Level 4 passenger

[3] The Cruise AV shuttle "Origin" is ready for mass production and deployment in the near future (https://getcruise.com/technology).
[4] Zoox AV is configured like a shuttle and presented by the company as intended for ride-hailing service (https://zoox.com/vehicle/).
[5] 2getthere has been deploying Level 4 shuttles for over 20 years (https://www.2getthere.eu/technology/vehicle-types/grt-vehicle-automated-minibus/). ZF is now presenting this technology as a key element of their offering of autonomous mobility (https://www.zf.com/mobile/en/technologies/domains/autonomous_driving/stories/20211124_autonomousshuttle.html).
[6] Shepardson, David. 2022. "GM seeks U.S. approval to deploy self-driving vehicles." *Reuters*, Feb. 18, 2022. https://www.reuters.com/business/autos-transportation/gm-seeks-us-approval-deploy-self-driving-vehicle-2022-02-18/).

service when operating in mixed traffic—as requested by General Motors.[7] A more substantive indication of NHTSA's posture on this issue could be forthcoming later in 2022–2023, prior to the intended initiation of passenger transport services with the Cruise/GM vehicle known as "Origin" planned for 2023.

NHTSA has also indicated that the safety of passengers inside the vehicle's passenger compartment is still central to their focus. Within the past 2 years they have issued directives that for shuttle vehicles originally designed to allow both seated and standing passengers, they may restrict the passenger occupancy to only seated passengers with seat belts when operating in mixed traffic. This assessment is an interpretation of a specific NHTSA directive issued in early 2020 for the Columbus AV shuttle deployment when a passenger was injured during an emergency brake of the vehicle. NHTSA subsequently extended this directive to all other deployments of this AV shuttle supplier, whether or not the vehicles were operating in mixed traffic. Refer to the update section on Columbus, Ohio, as one of the 10 early deployment sites, with details of the NHTSA directive given in Section 3.1.1.

1.3 Key Premise Concerning Optimization of Traffic Operations

Ultimately, the single most important factor for providing transportation with both increased safety and sustainable energy use can be described as "optimization of traffic operations" through AV technology applications in dense urban environments, where the high capital cost of automation can be most easily recovered in the business case for implementation. ***However, achieving this optimization will not be accomplished solely by deploying more and more AV fleet vehicles into the traffic mix.*** Rather, it will be accomplished by deploying connected AV fleets that have their operational performance optimized in terms of travel speeds and trajectories through the complex operating environment. Our premise is that this will require applying advanced sensing and artificial intelligence-based perception technology to the roadways as well as to the vehicles themselves to achieve robust, resilient, and fail-safe operation.

This speaks to the "system-level" view that is espoused in this document—a system that is larger than just the individual vehicle fleet and its automated control technology. The system being addressed in the sections that follow is in reality a "system of systems," encompassing the overall automated mobility system within an AMD that wraps around both the individual fleet vehicle technologies and the roadways.

An important initiative that is central to this connected and automated vehicle "system" concept has been underway within SAE in the work of the On-Road Automated Driving committee. This has borne fruit in the current standard SAE J3216 that defines cooperative driving automation (CDA) between individual vehicles and between vehicles and roadway infrastructure. CDA is a key element of the way forward that is described in the following sections. As part of that discussion, the SAE standard, along with the corresponding work of the U.S. Department of Transportation in the CARMA research initiatives,[8] are addressed below in greater detail.

[7] Wodecki, Ben. 2022. "GM's Cruise Seeks Commercial Deployment of Driverless EVs." *IoT World Today*, Feb. 23, 2022. https://www.iotworldtoday.com/2022/02/23/gms-cruise-seeks-commercial-deployment-of-driverless-evs/.
[8] Federal Highway Administration. 2022. "CARMA Program Overview." Last updated April 27, 2022. https://highways.dot.gov/research/operations/CARMA.

The principal benefit of optimized traffic operations within an AMD will be realized through the extra safety level of protection provided by the integrated vehicle/infrastructure system, which will allow the AV fleet vehicles to maintain higher speeds as they approach a roadway junction. The premise explored in the sections that follow is that this essential element of sustained speeds within the traffic flow can only be accomplished with intelligent infrastructure, without which slower speeds of AV fleet vehicles will result when depending strictly on the individual vehicle's sensing and perception capabilities. The essential achievement of a system with intelligent infrastructure assisting intelligent vehicles will be the capability to deliver AV operating speeds that are more fluid and sustainable at the higher speeds typical for arterial streets today with all traffic comprising conventional, human-operated vehicles. Fewer speed perturbations will occur as the mixed traffic of automated, self-driving AV fleet vehicles and non-automated, human-driven vehicles flow together on the approaches to the roadway intersections and through other roadway junctions. The important result will be optimized traffic operations with a corresponding reduction in energy use, and with fewer accidents in the critical safety zones around roadway junctions. The need for intelligent infrastructure systems is further amplified and underscored when coordinating and protecting the movements of vulnerable road users such as pedestrians and micromobility users.

2 What We Have Learned From AV Research and Deployment Pilot Projects

The first edition of the *AMD Implementation Catalog* was dedicated to reporting on the "Insight Gained from 10 Early Deployment Sites." These sites have progressed through a variety of different results and situations. Section 3 reports on the status of each of these 10 sites and the lessons learned over the past 2 years since the first edition was published.

2.1 Common Pattern of Progressive AV Development

NREL's research under this effort has been focused on part of the AV industry pursuing the provision of automated mobility for passengers in urban settings as a public service, rather than the part that is moving progressively through original equipment manufacturer applications of lower levels of automated driving assistance for private vehicles. This public mobility focus has been tracked through the 10 deployment sites primarily from the perspectives of the site owner or management entity as prototypes of automated mobility districts. It has been observed that there are common stages and patterns of development, often meeting failure or unexpected constraints. These hurdles have been commonly acknowledged, and renewed development and new partnerships have emerged to overcome the challenges and advance toward urban mobility goals. Common stages that have been observed across multiple early deployments can be summarized as follows:

1. **Vision for the Future** – Early concepts identified that provide a grand vision for the ultimate future AV deployment.
2. **Phased Deployment** – Progress through a phased development program that begins with simple goals and purposes to demonstrate AV technology.
3. **Adjustments for Unexpected Conditions** – Adjustments made in successive phases that address unexpected operational conditions and/or maturing AV technology limitations.
4. **Partnerships Essential for Progress** – Establishing essential AV developer and other industry partnerships to continue the progressive advancement, including pursuing funding, establishing contractual relationships, and reconfiguring the partnerships/relationships as some companies withdraw.
5. **Improve the Equity of Access** – Improving equity of access to the AV services for all passengers, including the elderly and disabled.
6. **Challenge of Preparing for Mixed-Traffic Operations** – Continually pressing toward meeting the challenge of fully automated Level 4 operations in mixed-traffic conditions with no operations personnel on board.
7. **Extended AV Service Within the City** – Preparing to extend the benefits of automated mobility beyond the early deployment site to reach larger areas of the city's urban core.

Not all deployment sites have addressed these stages and the associated challenges in the same way, nor at the same rate of progress or sequence. Some have, in fact, simply abandoned the effort to pursue AV deployments at this stage of the industry maturation when there are still such daunting challenges that must be met. For some early deployment sites, it was judged better to leave their pursuit and let others who are determined to climb the "mountain of research and development" push the industry forward.

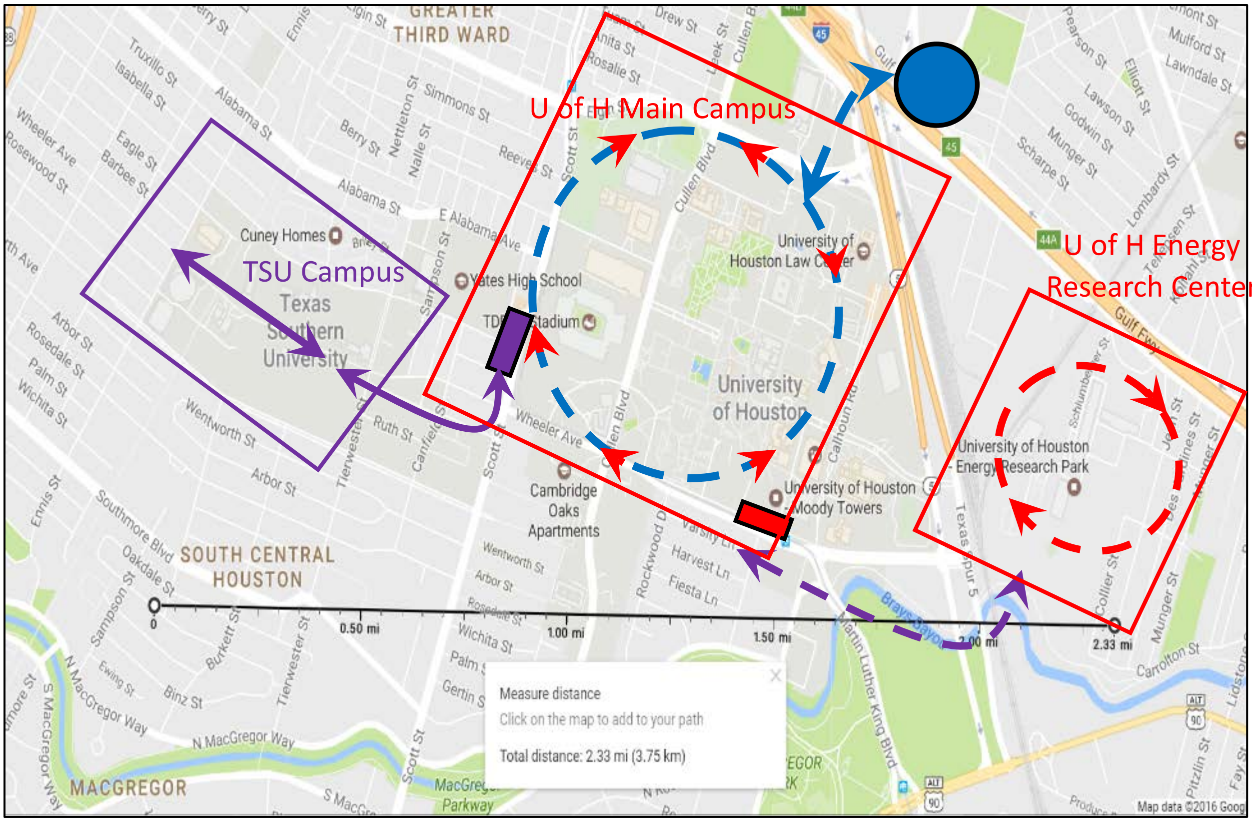
For purposes of introducing this discussion of what the industry has learned, the challenges faced by one such deployment site will be briefly highlighted as an example of these development stages and the way industry is advancing through the challenges. Houston, Texas, has been a strategically important site for AV development and continues to pursue the goals of automated mobility for all within the urban core community of this very large city. The University District AV circulator system has been an early AV transit deployment site that has seen progressive development over the past 5 years. The experience gained from this project, combined with the new initiative of deploying a full-size AV bus as part of the Automated Bus Consortium[9] initiatives, capsulizes the industry's experiences with AV research and development. A more complete report on the status of the University District is found in Section 3.5.

Vision for the Future – The Texas Southern University (TSU) Center for Transportation, Training, and Research in Houston, Texas, served as the principal investigator for a 2016–2017 Transportation Research Board study called "Regulations and Policies Impacting AV/CV Introduction in Transit."[10] This early research was well received, and the Transportation Research Board sponsored a national webinar on the topic in late 2017. The work resulted in developing the concept for a University District AV circulator system in late 2016 and forming a local partnership between TSU, the University of Houston (U of H), and Houston METRO in early 2017. Joining the team at an early stage was the city of Houston and the metropolitan planning organization Houston-Galveston Area Council.

Figure 2-1 shows the early grand concept of the ultimate AV circulator system as it has been envisioned to serve both the TSU and U of H campuses. Essential to METRO's interests are the strategically important first-mile/last-mile connections to several stations along METRO's Purple Line light rail transit (LRT) system, as well as a nearby transit center served by METRO's regional high-occupancy vehicle lane busway system.

Phased Deployment – Houston METRO embraced the idea of leading in AV research and development, and METRO funded the first phase of the project in the protected environment of the TSU campus. A request for proposals (RFP) was released to the AV industry in 2018, and the respondent selected for Phase 1 of the implementation was First Transit, teamed with the French AV developer EasyMile. The initial deployment was a single EasyMile EZ10 low-speed shuttle vehicle operated along a simple linear route within the TSU "Tiger Walk"—a linear pedestrian facility that bisects the campus. The route and the shuttle vehicle are shown in Figure 2-2. This shuttle ran with onboard safety attendants and carried students and faculty passengers along the TSU Tiger Walk between June 2019 and February 2020.

[9] The Automated Bus Consortium is described on its website as follows: "An association of transit and transportation agencies has formed the Automated Bus Consortium, a collaboration designed to investigate the feasibility of implementing automated bus projects across the United States." https://www.automatedbusconsortium.com/.
[10] Transportation Research Board. 2022. "Impacts of Regulations and Policies on CV and AV Technology Introduction in Transit Operations." The National Academies of Sciences, Engineering, and Medicine. Accessed March 23, 2022. https://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=3935.



Multifaceted Research and Development Program will occur simultaneously with the following implementation phases

TSU **Early Deployment Phase 1**	**Early Deployment Phase 2** LRT Station – Purple Line TSU/UH Athletic District
UH & ERC Connections **Early Deployment**	**Medium Term Deployment Phase 3** LRT Station – Purple Line UH South/University Oaks
UH Main Campus **Medium and Long Term**	**Long-Term** METRO Eastwood Transit Center Connection

Figure 2-1. University District phased transit circulator system grand concept—phased implementation of fixed-route shuttle and demand-response AV transport services.

Source: Google Maps and Texas Southern University Center for Transportation, Training, and Research

Figure 2-2. Houston University District Phase 1 Shuttle

Source: Houston METRO (left); TSU Center for Transportation, Training, and Research (right)

Adjustments for Unexpected Conditions – Operations ceased in February 2020 when NHTSA issued a temporary order to cease all EZ10 operations at demonstration sites across the United States. The order was sustained while an incident that occurred in Columbus, Ohio, was investigated further, continuing until safety-related modifications were made to the vehicle (see the related discussion in Section 3.1).

This cessation of service was immediately followed by the closure of the TSU campus during the COVID-19 pandemic, and Phase 1 operations of the University District AV circulator never resumed. These experiences were typical for all AV demonstration pilots, with NHTSA's directives affecting some projects and the impact of the 2020 pandemic shutdowns resulting in a cessation of passenger service affecting all projects.

Partnerships Essential for Progress – The assessments made by Houston METRO and the partnership agencies led to new vehicle specifications for the second phase of demonstration—one with an emphasis on improving accessibility to the AV services for METRO passengers from the disabled community. Houston METRO led the pursuit of a Federal Transit Administration (FTA) Accelerating Innovative Mobility (AIM) grant to fund this next phase, which was awarded in June 2020. However, the grant funding delivery process, contract negotiations among the project participants, and preparations for the early prototype vehicle development extended the time into early 2022.

The specific Houston METRO grant award project team currently includes Houston METRO (recipient), Phoenix Motorcars, and AECOM for this Phase 2 project. The team is contracted to develop a new prototype AV technology on the vehicle platform shown in Figure 2-3, called the Zeus paratransit bus, manufactured by Phoenix Motorcars. This is a battery-electric vehicle that is fully compliant with both FMVSS and FTA's Americans with Disabilities Act (ADA) regulations for this class of vehicle. Refer to Section 3.5 for more information on this vehicle.

However, at the beginning of 2022, as METRO was negotiating contracts with its team members following the grant award, a fourth company that had been tasked with providing and installing the ADS kit in the Zeus battery-electric bus unexpectedly withdrew from the team. The reason was a change to the company business plan that was refocusing on the cargo and freight market, rather than passenger transport. This sudden loss of a strategically important team member has resulted in METRO initiating an RFP process for the ADS supply, installation, and testing, after which the project will continue later in 2022.

Improve the Equity of Access – The operating route for the Phase 2 deployment has been under development with the larger team of universities and governmental agencies throughout 2020 and 2021. The routes being assessed by Houston METRO and its partners provide the desired connection between the TSU campus, the U of H campus and the METRO LRT station located between the two campus areas. But with the AIM grant funding emphasis, the routes are also being evaluated by the project team with respect to providing access for the economically depressed community of Houston's Third Ward that is adjacent to the University District. Several of the routes being considered extend to reach Cuney Homes—a historic public housing community that would be directly linked to the LRT station. Other aspects of the alignment are also being discussed that connect portions of the U of H campus more effectively.

Challenge of Preparing for Mixed-Traffic Operations – The route options shown in Figure 2-4 each place different requirements on the capabilities of the ADS technology supplier. The challenge of providing a route that does not require the AV buses to make an unprotected left turn across conflicting traffic movements is a very important consideration in the route planning process, since the current level of development for almost all ADS technology would require the onboard attendant to take control to perform this type of maneuver.

Also of major importance is the necessity of vehicle-to-infrastructure (V2I) communications at the point that the route would cross the LRT system tracks. This signaling system coordination and related roadway infrastructure will require communications links with the AV shuttle as it is operating through these particularly complex intersections. This critically important coordination of multiple signaling systems and the related control of AV movements is discussed in more detail in Section 3.5.

Extended AV Service Within the City – There has been one other aspect of Houston METRO's initiative to bring AV transport to Houston that has taken shape during the past 2 years. METRO was one of the founding members of the Automated Bus Consortium. Once the procurement solicitation by the consortium is complete, METRO will then decide whether it wants to further pursue a purchase of one or more of the first full-size AV buses for testing and deployment. Figure 2-5 shows the route on which the first AV buses will be operated between downtown Houston and the Memorial City Mall location. The AV bus specification has been completed by the Automated Bus Consortium, and an RFP process is nearing completion at the time of this document's preparation. Multiple AV bus suppliers are expected to be prequalified by the Michigan Department of Transportation, which is the lead agency throughout this consortium procurement process. Houston METRO's Memorial City route is a premier early deployment that the consortium will be showcasing, and procurement of its initial AV bus is planned for later in 2022. The current project schedule calls for AV bus manufacturing and closed-course testing during 2023–2024, followed by the initial testing on the operating route in 2025.

Figure 2-3. Houston University District Phase 2 battery-electric paratransit bus—Phoenix Motorcars Z400 electric shuttle.

Source: Phoenix Motorcars

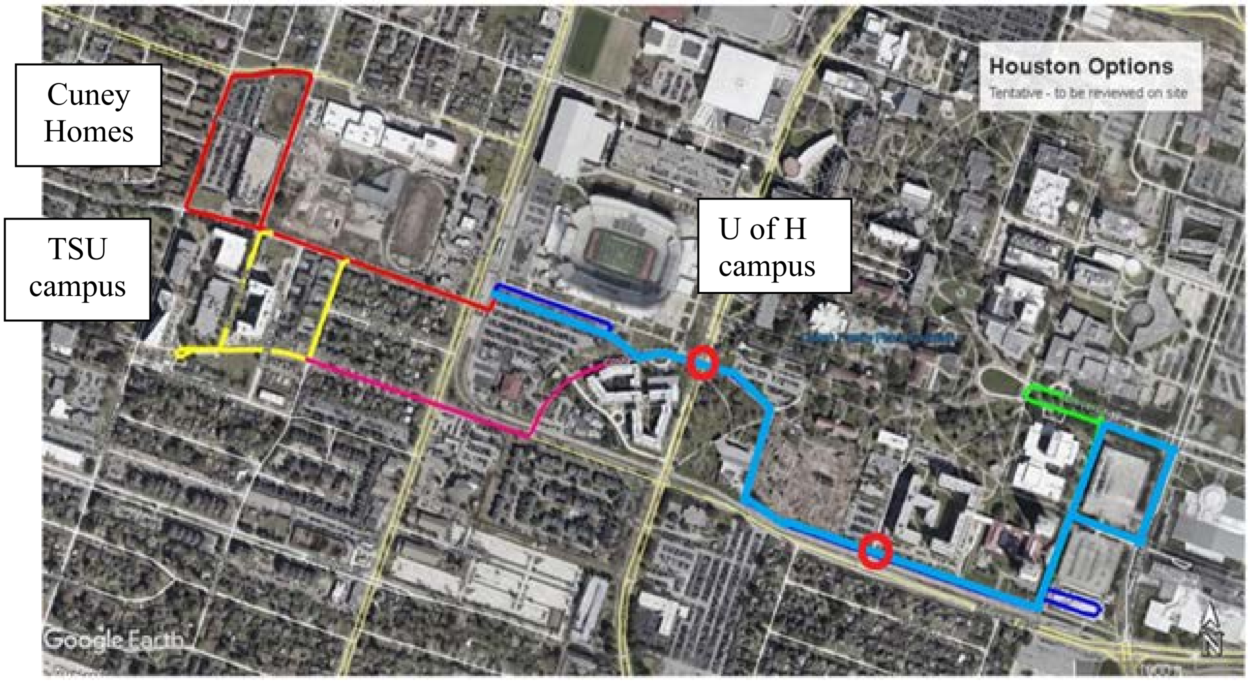


Figure 2-4. Houston University District possible route options for Phase 2.

Source: Houston METRO

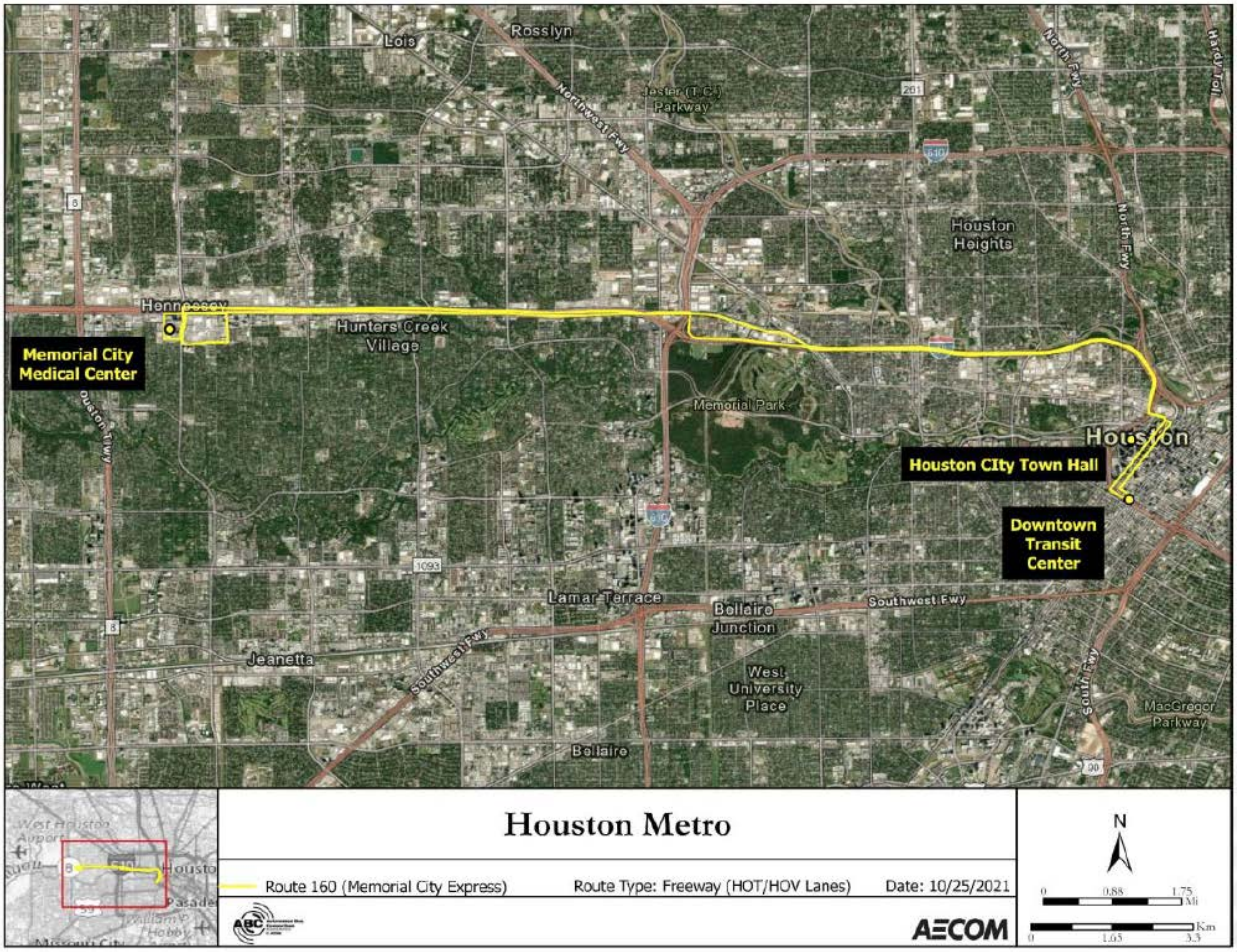


Figure 2-5. Houston METRO's first full-size AV bus deployment will occur on the Memorial City Mall route, with Level 4 self-driving operation planned within the high-occupancy vehicle dedicated lanes of the route along Interstate 10.

Source: Automated Bus Consortium website (accessed March 23, 2022)

2.2 Challenges Faced by Early AV Research and Development Initiatives

These experiences of the Houston METRO and its partner agencies with the University District AV circulator pilot deployments are common to many of the early AV deployment sites. Beginning with a grand concept of how AV technology will serve a complete district with diverse automated transport services, the reality of taking "baby steps" through the early R&D phase of ADS technology deployment has pushed back the timeline that was first anticipated for many projects.

A prominent factor among the early deployment sites has been the restrictions that NHTSA has placed on the operations of the low-speed AV shuttle class of vehicles when they do not satisfy the FMVSS criteria met by conventional automobiles and buses. The NHTSA stipulations for importing noncompliant AV shuttle vehicles from several overseas manufacturers has only allowed their entry into the United States for test and demonstration pilots. Using the "Box 7" provision for temporary exemption from compliance with FMVSS and the associated operations and use restrictions has been a major factor in the early deployment initiatives. Appendix A has an example of the NHTSA restrictions in place for the EasyMile EZ10 deployment currently in operation in Gainesville, Florida (refer also to Section 3.9).

Even the FMVSS provisions for low-speed vehicles that were originally developed for golf carts and which are now applicable to a variety of lightweight vehicles with a maximum speed capability of 25 miles per hour (mph)—such as the Polaris GEM electric vehicles—have not been allowed for application to the vehicles of several prominent AV developers. The disqualification of vehicles like the EasyMile EZ10 low-speed shuttle is because this class of AV technologies is typically heavier than the maximum weight criteria in the FMVSS low-speed vehicle requirements.[11]

Another challenge commonly revealed by early pilot projects has been the policy-level requirements that add complexity to the R&D—such as accessibility for the disabled population in accord with ADA regulations. The challenge comes when addressing these policy goals while still keeping the ADS development moving in incremental steps, and while also keeping the vehicle design simple and efficient.

Even with these significant challenges at many of the early deployment sites, much has been learned over the past 5 years. There is a growing body of knowledge about how AV technology will fit into our urban transportation landscape, and what needs to change in AV technology design and capabilities in order to integrate well into dense urban settings.

These accomplishments and advances are found across many of the 10 early deployment sites that are updated in Section 3, most of which are moving into their second and third phases of deployment.

2.3 Findings and Observations From the 10 Early Deployment Sites

The following points of discussion are drawn from the last 5 years of monitoring the progress of the 10 early deployment sites documented in the first edition of the *AMD Implementation Catalog series*, and from their updated status reported in Section 3 that follows. These observations are also generally representative of the findings from tracking the many more AV industry deployments that have also occurred during that same period. And as noted above, these findings were current as of April 2022.

Numerous Demonstration Pilots – There have been numerous sites at which AV technology has been deployed. The following vehicle types have been equipped with ADS sensors and control technology in these various R&D initiatives:

- Low-speed, lightweight vehicles with designs complying with FMVSS 500 Series standards.
- Purpose-built low-speed shuttle vehicle designs; this class of vehicles has been common in early deployments, but is generally noncompliant with FMVSS.

[11] The FMVSS low-speed vehicle standards are generally referred to as the "500 Series" requirements (https://www.govregs.com/regulations/expand/title49_chapterV_part571_subpartB_section571.500).

- Conversions of conventional automotive vehicles (i.e., intentionally designed to meet all FMVSS requirements) by retrofitting the vehicles with sensor stacks and ADS kits.
- Conversions of buses and paratransit vehicles by retrofitting sensor stacks and ADS kits (these are the latest AV applications currently in development).
- Purpose-built, four- to six-passenger, shared-ride AV "shuttle" vehicles designed to be FMVSS-complaint, except for having no steering wheel, brake pedal, or rearview mirrors.

Almost all these deployments have been limited to maximum operating speeds of 15 to 25 mph. For some Phase 1 deployments, such as the AV shuttle on the TSU campus that operated back and forth along a fixed route in a protected environment, lower maximum operating speeds of 8–10 mph were common since the shuttle was operating in a primarily pedestrian environment, but also encountering an occasional bicycle or skateboard.

Managed Fleet Operations – For all deployment sites, the operational methods employed have an association to what this document refers to as "managed fleet operations." In some cases in the early deployments, the "fleet" was only a single vehicle, but most consisted of a few vehicles or more. The basic fleet management with a supervisory system allowing operational monitoring from a remote operations center was common, even for the demonstration pilot deployments with single vehicles in passenger service. Fundamentally, all of the supervisory systems are designed to allow the system to scale up as vehicles are added to the fleet operation and as the service area is expanded over time.

It is notable that the supervisory control system framework for fully automated transport systems is well established, having evolved from the last 50 years of industry design of automated people mover systems such as those common in large airports, and in the last few decades even regional-scale automated fixed-guideway mass transit systems. Further, this system-level management by a "fleet operator" is consistent with what has been observed in the early AV deployment site pilot projects, where the day-to-day management of the system is contracted through operating companies that are experienced in operating conventional public transit systems.

Roadside Infrastructure as an Element of AV Control Systems – A significant percentage of early AV deployments have relied on a form of roadside infrastructure to sense some aspect of the dynamically changing roadway environment when the automated vehicles are moving through mixed traffic. The continuous communication of information about these dynamic conditions to the AV fleet vehicles as they approach roadway junctions typically is designed to protect the vehicles and their occupants in complex conditions where there is a convergence of other conventional human-driven vehicles, pedestrians, and active transportation roadway users, or combinations of these modes. These applications of roadway infrastructure, which are essentially designed to be integrated as a part of the AV fleet's operational control system, have been observed or noted in the planning of the latest phases of deployment sites in various forms that include:

- Traffic signal phase, and in some applications the real-time status of signal timing and the pending change of signal phase (e.g., 5 seconds until a signal change from green to yellow)—commonly called signal phase and timing ("SPAT") data.

- Operational state of other transportation systems that have occasional conflicting movements to the AV fleet vehicles (e.g., at locations where other transit vehicles have traffic signal preemption priority, or locations where the AV fleet vehicles cross fixed-rail systems).
- Pedestrian presence/proximity to roadway lanes, or where pedestrians are permitted entry to cross roadway travel lanes where AV fleet vehicles are operating.

Fixed-Route Transit – For most of the early deployments, the operational configuration of the AV services has been along a fixed route using dedicated lanes, thereby providing a less complicated operating environment with limited traffic interactions. This simplified operating approach is gradually being replaced, with some AV fleets now beginning to operate along a fixed route in mixed traffic as the R&D initiatives advance the maturity of the vehicles' automated driving systems.

Demand-Response AV Services – Some of the AV developers are now providing on-demand dispatching of the AV fleet vehicles to pick up passengers at a specific origin location and to then take them directly to a specific destination location—a service that is generally called "mobility-on-demand" or "on-demand transit." With the common experience of "hailing a taxi" now being redefined by the taxi-like operational concept of transportation network companies (TNCs) such as Uber or Lyft, a term with growing popularity for AV applications is "robo-taxi." The challenge of developing AV technology that can safely negotiate a large roadway network creates a practical limitation of exactly where the vehicle can come to a stop at a curbfront to allow passengers to safely enter and exit the vehicle. For that reason, AV developers are typically defining dedicated curb or station stops as the specific pickup locations for passengers boarding and alighting the vehicles.

Experimentation and R&D – Research and development work continues as many sensor stacks, software algorithms, localization methodologies, and artificial intelligence perception packages are being tested and refined. In addition, the vehicle platforms in which ADS kits are being installed appear to be evolving toward acceptable designs that will meet NHTSA approval for street operations in mixed traffic. Also observed are efforts to increase the vehicle's operating speed and improve its passenger comfort features.

Preparations to Manage Unexpected Changes – AV deployments of any scale and complexity will benefit from having a written project mission statement and service objectives, along with an associated "operational concept" description. This documented baseline of what is intended to happen when AV service begins ensures that all parties have common expectations and reference points, including the projects owner/sponsor, the AV technology provider, the first responders and police, the state and local transportation agencies having jurisdiction, and any federal funding partners and regulatory agencies. With all parties working from this Project Operating Plan, any changes required while the AV deployment is in service will be much easier and faster to accomplish. Examples noted for the 10 early deployment sites show that the parties involved can make faster pivots to a new plan, whether these are major changes like a passenger route alignment change or a nuanced customer service change, such as a different boarding location within a particular city block that better serves passenger trip patterns.

2.4 AV Industry Indications of Challenges and Next Steps

So the important question that can be asked is, *"Where do we stand at this point in time with AV technology development?"*

AV developers are sending signals that there still must be limitations to the complexity of operating conditions, combined with a realistic lowering of expectations of what an individual automated vehicle can do when operating in dense urban settings. The following are becoming the typical explanation of the conditions under which AV deployments can continue to advance.

ODDs – The ODD definitions for more advanced AV operations remain constrained and focused on deployments in certain climates (absent of snow and ice) and in less complex roadway traffic conditions.

Delivery of Level 4 Operations – Due to the complexity of providing safe transport of people in dense urban environments, the automated vehicle industry's goal for broad deployments of large AV transport fleets have been pushed back in time. The challenge of operating vehicles that are completely "unmanned" by dedicated operations personnel (e.g., without "safety attendants" on board) has proven to be a greater challenge than first believed. Although a few examples could be cited of unmanned vehicle operations in very controlled circumstances, the growth and expansion of Level-4 deployments has not met either the initial societal expectations or the "marketing department" forecasts of the AV developers. This goal remains as one very important objective to achieve, since the very cost-efficient operations of unmanned vehicles is the foundation of the return-on-investment business case for AV technology development and deployment in public transport service.

Concepts Being Offered To Simplify the Operating Environment – Due to these complexities and challenges that the AV developers are facing, the following are ideas offered and discussed in industry forums as ways to deliver AV technology in the near to medium term:

- Limitation of AV operations to dedicated lanes
- Operation of AVs at low speeds, even in mixed-traffic conditions
- Authorization of only a single AV technology for operations in a given district
- Retention of safety attendants in the most complex environments to provide human operation through the "tough spots."
- Designing in the ability for remote operation—often called "tele-operation"—such that the safety operators can take control of a vehicle from an operations center when needed to perform manual operations.

These ideas being communicated by AV developers all point to their recognition that there is a need for a more sophisticated perception and control system in order to deploy large-scale AV fleet systems in complex operating environments while maintaining safe and efficient mobility transport services. The following proposed solutions are being discussed in industry forums as ways to mitigate the challenges of complex operating environments:

- **Seeing around corners** through vehicle-to-vehicle (V2V) communications in real time.
- **Infrastructure assist** for sensing and control functions, with vehicle-to-infrastructure (V2I) communications using roadside units (RSUs) and onboard units (OBUs)—thereby

expanding the capabilities of the control system to sensing and control functions outside of the individual vehicles.

- **"Geo-net" operations** where the AV fleets operate on a limited network of selected roadways, rather than "geofenced" operations defined by a simple boundary of an entire area within which AV fleets operate on all roadways inside the geographic "fence."

Equally revealing are comments heard in industry forums from experts in AV technology applications and the investors who are tracking the progress of AV developers. Recent talks have had comments like:

- It could be a decade or more before privately owned AVs are ready to drive themselves long distances without anyone onboard.
- Fleet operations will dominate the AV landscape for the near to medium term.
- Infrastructure will be key to mitigating the hazards and risks for AV applications.

Many of these signals from AV development industry insiders seem to indicate that they are realizing the operational control systems must expand beyond the sensing, perception, and artificial intelligence making contained decisions strictly within each individual vehicle.

Yet there are some AV technology developers who remain committed to developing their product to be independent of any other "external" technology applications. This debate will continue to progress as AV fleets begin to be deployed beyond the test environments and into urban district deployments with much more complicated operating environments and more challenging passenger-trip demands.

2.5 Considering the Benefits of Cooperative Driving Automation

The automotive industry overall is beginning to recognize that if fully automated, driverless vehicles are to safely maintain their performance at a level suitable for safe operations in mixed traffic, the actional information from "outside" the individual AV fleet vehicle's sensing capability will be important to provide. SAE, which provides a forum by which consensus can be found on such issues, proposed the role of infrastructure and communications in AV deployments as a means to create higher performance levels like maintaining intersection approach speeds while maintaining safe operations.

SAE has already taken initial steps to create the framework for industry consensus on the concept of a larger integrated control system under the banner of what they call "cooperative driving automation." SAE standard J3216, "Taxonomy and Definitions for Terms Related to Cooperative Driving Automation for On-Road Motor Vehicles," has been developed by SAE's On-Road Automated Driving committee to begin this consensus development.

The introductory scope given in the updated standard J3216_202107 states the following:

> *"This document describes machine-to-machine (M2M) communication to enable cooperation between two or more participating entities or communication devices possessed or controlled by those entities. The cooperation supports or enables performance of the dynamic driving task (DDT) for a subject vehicle with driving automation feature(s) engaged. Other participants may include other vehicles with driving automation feature(s) engaged, shared road users (e.g., drivers of*

manually operated vehicles or pedestrians or cyclists carrying personal devices), or road operators (e.g., those who maintain or operate traffic signals or workzones)."

The principle of automated vehicles "cooperating" with other vehicles and with roadway infrastructure has already been established in this standard through SAE's industry working committees. The latest version of the standard defines the following four "classes" of cooperative driving automation:

A. Status-sharing CDA
B. Intent-sharing CDA
C. Agreement-seeking CDA
D. Prescriptive CDA.

The principles of CDA are most applicable to vehicles that have an ADS operated exclusively at Level 4 or 5 automation within their established ODDs. SAE J3216 uses the term "ADS-dedicated vehicles" to indicate this high level of automation.

SAE defines Level 4 automation as providing sufficient automated control to safely operate without a driver or even a safety attendant, as long as the vehicle stays within a geofenced area established in the ODD. As sometimes referred to in popular vernacular as Level 4 "autonomy," this level of automation allows the vehicle to operate within suitable design constraints of weather/environmental conditions, and in some sense within the design limits of safety as a function of traffic conditions.

Further to these industry consensus initiatives to define cooperative driving automation principles, the federal government is also actively involved in advancing the CDA state of the art. Through its CARMA initiative, the U.S. Department of Transportation is fostering an open-source community of developers to provide appropriate open-source software development that is suitable for executing the CDA principles. CARMA's focus is at both the research and development level, as well as to create a foundational CDA capability for industry to build on.

Based on the findings and observations of early AV deployments described above, and on the principles of cooperative driving automation, the authors put forward that an additional necessary element of an AV fleet operational control system will be required in the form of intelligent roadway infrastructure (IRI). Whereas current roles for infrastructure are limited to providing signal phase and timing (SPAT) and to serve as a communications relay for vehicle-to-vehicle (V2V) and vehicle-to-everything (V2X), the concept of IRI expands the functional role of infrastructure to achieve sensing, perception and control in a way that protects AV movements through complex intersections. This concept of IRI embeds in the roadway infrastructure sufficient spatial intelligence technology to create and disseminate a verifiably accurate digital representation of all movements for both roadway vehicles and vulnerable roadway users within the field of view. Such advanced technology infrastructure will be essential to achieving a near- to medium-term implementation of fully automated public mobility systems within large, operationally complex urban districts and major activity centers, providing the necessary redundancy for fail-safe operations while maintaining a high level of performance.

Part 3 (Sections 4, 5 and 6) of this document expands on IRI, providing a practical view on the future of large-scale AV fleet operations in dense urban environments in light of these conclusions. Intelligent roadway infrastructure is a central theme of this vision of the future. The premise that there is an essential need for IRI, as well as jurisdictional role in managing multiple fleets delivering AV mobility services, is thoroughly discussed as an extension of the observations on the development trajectory for continuing AV deployments. The concepts in the later sections address a combination of views from industry consensus on the need for CDA features, as well as design principles drawn from the last 50 years of automated fixed-guideway transit control system implementations.

Part 2: 10 Early Deployment Sites as Prototypes of AMD Implementation

- **Site #1: Columbus, Ohio**
- **Site #2: Arlington, Texas**
- **Site #3: Las Vegas, Nevada**
- **Site #4: Jacksonville, Florida**
- **Site #5: Houston, Texas**
- **Site #6: M-City, University of Michigan**
- **Site #7: Rivium, City of Capelle aan den Ijssel, Netherlands**
- **Site #8: Denver, Colorado**
- **Site #9: Gainesville, Florida**
- **Site #10: Babcock Ranch, Florida**

3 Status Updates on 10 Early Deployment Sites

During the 2 years since the first edition of the *AMD Implementation Catalog* was published, the 10 AV pilot projects that were highlighted have undergone considerable changes. Some of the early deployment sites have advanced to a new phase of operations with the same AV technology, and some with the same AV developer but a new vehicle platform. Others have entered the next phase of pilot projects deploying a wholly new AV platform, with a new AV technology developer now involved. Still others have ceased operations at the original site but are directly affiliated with other nearby and related site deployments that extend the AV applications and their scale of deployment.

All 10 sites were directly impacted by the COVID-19 pandemic and the resulting shutdown of public spaces in 2020. The continuation of the AV research and development progress of some areas was directly impacted.

Several sites were also affected by the NHTSA cessation-of-operations directive for the EasyMile EZ10 vehicle platform, which lasted for a few months during early 2020 while modifications were undertaken to improve passenger safety on board the vehicles.

The following subsections provide updates on each of the sites, summarizing what has transpired and what is the current status (as of April 2022) of the site's AV deployment. Related new appendices are noted in the sections, where applicable.

Reference to the first edition of the *AMD Implementation Catalog*[12] is useful and recommended to understand the full progress that has occurred at each deployment site.

3.1 Site #1: Columbus Update – Linden LEAP AV Shuttle

The Columbus Smart Cities program has produced a series of AV shuttle demonstration pilots that represent much of the evolutionary progress and the range of challenges that the whole of the AMD early deployment sites have experienced. Further, the overall Smart Columbus program was quite broad, and the AV shuttle component was integrated with a number of other initiatives, as can be found on the Smart Columbus website maintained by the city of Columbus.

Columbus was the original recipient of the 2016 Smart Cities Challenge grant award from the U.S. Department of Transportation, and as part of that grant process, several phases of AV shuttle demonstration pilots were completed. The first was the Smart Circuit, a 1.4-mile loop alignment in downtown Columbus that deployed six May Mobility Polaris GEM shuttles to connect between points of attraction in the Scioto Mile district. The Smart Circuit pilot project that launched in December 2018 concluded its operations at the end of September 2019. This initial AV shuttle demonstration project was described in the first edition of the AMD Implementation Catalog of 10 deployment sites.

The second-phase AV shuttle demonstration pilot had been in planning since community workshops identified its need in January 2018, with service beginning in February 2020. Known as Linden LEAP (Linden Empowers All People) and shown in Figure 3-1, the original route

[12] Young and Lott. 2020. *The Automated Mobility District Implementation Catalog*. https://www.nrel.gov/docs/fy20osti/76551.pdf.

provided passenger transport services to essential destinations for residents of this special opportunity neighborhood.

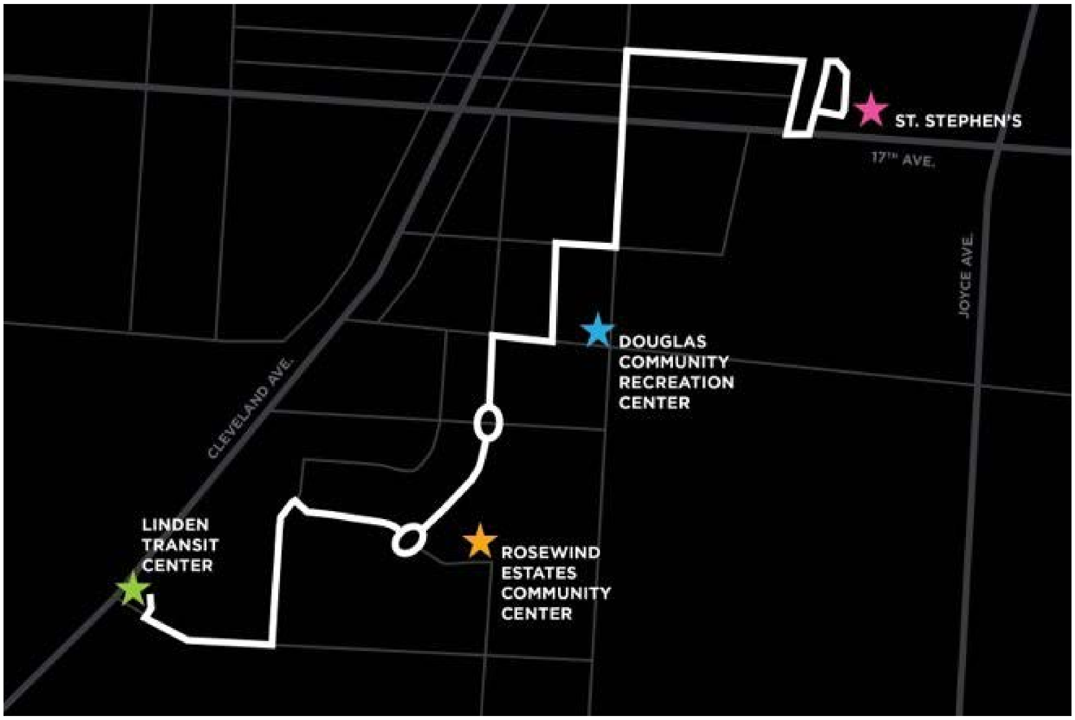


Figure 3-1. Original Linden LEAP AV shuttle alignment for passenger service.

Source: City of Columbus

The city of Columbus determined early in the pursuit of the federal grant that the application of AV technology would be to accomplish the overarching goal as stated on the Smart Columbus website: "use self-driving shuttles to close transportation gaps to reaching public transportation, affordable housing, healthy food, childcare, recreation and education." Local publicity noted that the service was the first public, daily operating self-driving shuttle in a residential area in the United States.

To accomplish this goal, the AV shuttle service deployed two EasyMile EZ10 Gen 3 vehicles along a route that connected the Linden Transit Center with several important locations providing essential services to this transit-dependent community. In particular, the route helped to solve "first-mile/last-mile" mobility challenges in reaching the transit center, as well as destinations providing the Linden community access to resources of affordable housing, childcare, and recreation. Also of strategic importance to the ultimate deployment of the shuttles was the direct connection to the St. Stephen's Community House. This community-oriented service center provides the Linden community with a food and nutrition center, youth-focused activity programming, and a health center.

The EasyMile vehicles deployed between February 2020 and April 2021 are shown in Figure 3-2. Contracting with EasyMile as the Linden LEAP AV shuttle technology provider was accomplished through a competitive procurement and selection process.

Figure 3-2. EasyMile Gen 3 vehicles that operated the Linden LEAP service.

Source: City of Columbus

However, early in 2020, the impacts of the COVID-19 pandemic and the shutdown of almost all aspects of public life resulted in a situation where the deployment of the EasyMile shuttle vehicles had to be rethought. The temporary safety-related cessation of public transport service that occurred in mid-February due to an NHTSA-initiated directive (see the discussion in Section 3.1.1) was overshadowed by the concurrent onset of the pandemic that required a more complete reassessment of the automated shuttle's use case during the remainder of the demonstration pilot.

The city of Columbus team developed a creative alternative use case for the EasyMile shuttles' deployment within the community through an application that retained their use to fulfill some aspects of the overarching goal noted above. The solution was an AV shuttle application of goods movement that assisted the distribution of prepackaged food from St. Stephen's to the Rosewind Estates public housing community, thereby retaining the alignment that had been approved by NHTSA for shuttle service in mixed traffic.

Figure 3-3 illustrates the refined and truncated route for the AV shuttle's use to bring prepackaged food to the Rosewind Community Center Station, where the food was picked up by the local residents (Figure 3-4). The connection to the Linden Transit Center was not useful during the pandemic, as the public transit service levels were greatly reduced by the Central Ohio Transportation Authority (the public transit agency for Columbus) throughout the remainder of the scheduled demonstration pilot, and the need was to deliver food into the residential area.

This creative repurposing of Linden LEAP allowed the cost-share component of the grant award to be used in fulfillment of the project goals, while maintaining the pilot project objectives to demonstrate automated shuttle deployment in an important opportunity neighborhood identified by local Columbus leadership.

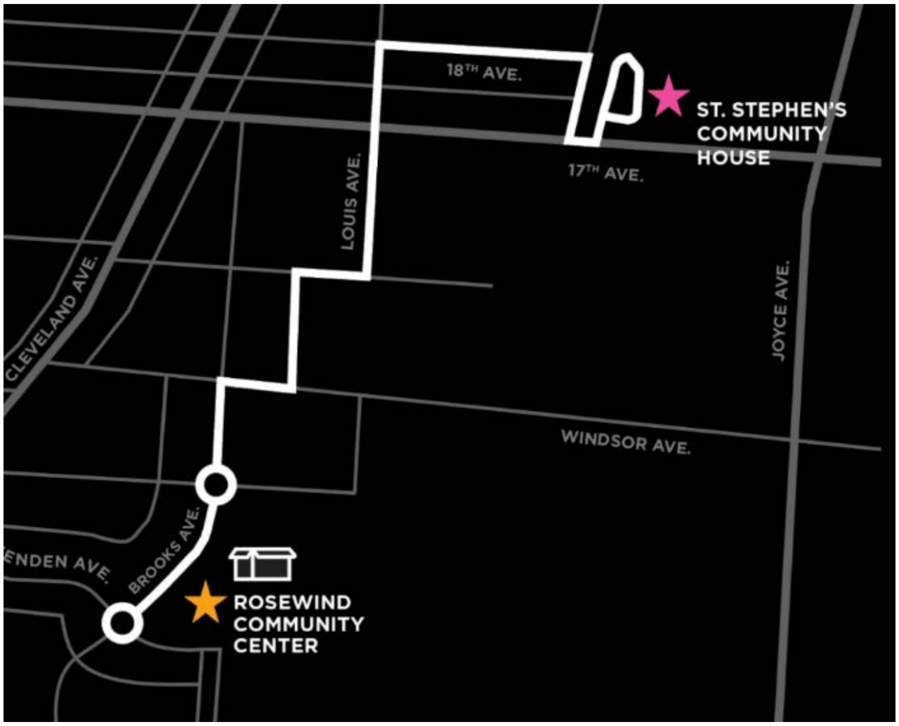


Figure 3-3. Truncated route for AV shuttle use to carry prepackaged food during the pandemic.

Source: City of Columbus

Figure 3-4. Linden line shuttles made food deliveries from a food pantry to families at Rosewind.

Source: City of Columbus

3.1.1 Challenges Faced and Lessons Learned

Several challenges faced by the Linden LEAP AV shuttle demonstration pilot created several valuable lessons learned. The following three critical lessons learned are covered in this section, with more insight to be gained from the full reports prepared by the Smart Columbus project team. For more information on these and other lessons learned, refer also to the next subsection, where a list is provided of reports, databases, and online resources that the city of Columbus has developed in fulfillment of the Smart Cities grant objectives.

NHTSA Directive To Cease Operations – Fifteen days following the initiation of the AV shuttle service in February 2020, one of the Linden AV shuttles performed an emergency stop when the onboard sensors detected an unsafe condition within the operating realm of the vehicle. This emergency stop, or “E-stop” action by the automated controls—which is intended to be an essential safety response to such conditions—resulted in a seated passenger sliding off the seat and onto the floor of the vehicle.

An incident report was promptly submitted to NHTSA for review. All such incidents are required to be reported as a condition of NHTSA’s permission for the operation of the imported EasyMile vehicles, which do not fully comply with the FMVSS. As a result, NHTSA issued a “cease operations” directive to not only the Columbus Linden LEAP, but also to all properties and agencies operating any EZ10 vehicles throughout the United States.

The City of Columbus convened an incident review panel of independent experts to review information and recommend mitigations, and cooperated with NHTSA’s review of the incident. After several weeks of reviews, NHTSA issued its directives to make several changes to the vehicles, including the installation of seat belts for required use by passengers on board the vehicles when in operation. These recommendations were very similar to those recommended by the Columbus safety panel.

EasyMile promptly entered the design process of retrofitting the vehicles in accord with the directive, and after about 1 month of design and fabrication of the parts and software changes, the modifications were made by EasyMile on-site in Columbus. However, as previously described, by the time EasyMile provided required retrofits, the pandemic had caused the shutdown of public services in general, including many aspects of public transportation. The vehicles never returned to passenger service due to the concerns with maintaining social distancing in the small shuttles amid the ongoing pandemic.

One aspect of the lessons learned through this incident and the NHTSA directives was that passengers on board a driverless shuttle should be reminded of certain safety concerns when vehicles are in operating environments where sudden braking may occur. Specifically, for this case of the Linden LEAP E-stop incident, NHTSA included in its directive that passengers should not be allowed to stand while the vehicle is in motion. This has implications for the planning assumptions made concerning vehicle capacity when future vehicle operations will occur in mixed-traffic conditions.

Reimagining of the Linden LEAP Purpose – Columbus reassessed how to redeploy the EasyMile AV shuttles following the pandemic “shutdown” for food delivery, as previously described. The process to determine a new use case for Linden LEAP was actually a continuation of the initial development of an “operational concept” at the beginning of the project. Having established specific goals as part of the mission statement for the automated shuttle deployment, the city of Columbus was able to adeptly pivot to food delivery as one the essential goals of the original Smart City Challenge vision, as well as to stay within the bounds of the original NHTSA waiver approval from the FMVSS requirements.

This approach to project planning and execution reaffirmed that having written statements of the purpose and objectives for a project—even a demonstration pilot project—provides a foundation on which new forms of the deployment can be successfully “reimagined,” if necessary.

Route Configuration for Unidirectional Vehicles – The final lesson learned concerns the operating route with respect to vehicle design constraints. An operational constraint of the EasyMile Gen 3 vehicles (one that reduced cost of the system) was automated operation in only a single direction, retaining full performance of the propulsion system—what will be referred to here as a "unidirectional" design.

Note that this unidirectional design is not to imply that the vehicle was incapable of a backing maneuver, but that this reversal would require an operator to perform the maneuver under manual control. When the route was truncated to perform the new use case of goods delivery after the pandemic occurred, this unidirectional property came into play. As can be seen in Figure 3-3, the reversal of the vehicle at an existing traffic circle allowed automated operations to be quickly configured to establish a new end-of-line station at the Rosewind Community Center Station without a backing maneuver when relocated from the original Linden Transit Center Station, as shown in Figure 3-1.

The lesson learned from this rapid reconfiguration of the operating route was that the unidirectional vehicle design requires special provisions for reversing of the vehicle direction. This factor is important when creating a truncated route configuration for the automated shuttle—analogous to the reversal of a conventional bus, which requires significant space to "turn around" in order to reverse direction. Without the convenient traffic circle feature of the original alignment, a new route alignment for automated operation would need to have been approved by NHTSA. If changes to the route were required, additional vehicle route-mapping, programming, and recommissioning would also follow. Such changes would have resulted in substantial delays and potential project cost impacts.

3.1.2 Reports and Reference Documents

- Final report is scheduled for release during the summer of 2022.
- City of Columbus. 2019. *Connected Electric Autonomous Vehicle (CEAV) Operational Concept*. Columbus, OH: Smart Columbus. https://d3hzplpmmz6qe4.cloudfront.net/2019-07/Smart%20Columbus%20Connected%20Electric%20Autonomous%20Vehicle%20Operational%20Concent.pdf.
- City of Columbus. 2020. *Connected Electric Autonomous Vehicle (CEAV) Operational Concept: Appendix A – Alternative Use Case*. Columbus, OH: Smart Columbus. https://d2rfd3nxvhnf29.cloudfront.net/2020-08/SCC-B-CEAV-OpCon-APPENDIX_A-clean.pdf.

3.2 Site #2: Arlington – RAPID On-Demand AV Car Service

Arlington, Texas, was one of the very first municipalities to enter their own research program for the assessment of AV technology deployments using low-speed shuttles. The Milo project was deployed in 2017 to serve the multiple professional sports venues there—a program that was described in the first edition of the AMD catalog. Further, Arlington was one of the first municipalities to also advance its research to include applications of automotive-class AVs for public mobility in a subsequent research phase contracted to Drive.ai. As conveyed in the first edition, Drive.ai was unexpectedly taken over by Apple, shutting down Arlington's second phase in 2019.

The city of Arlington was then awarded an Integrated Mobility Innovation grant in early 2020 by FTA to continue with a third phase of research. The program deployed AV automotive technology under the RAPID (Rideshare, Automation, and Payment Integration Demonstration) initiative. This phase of the AV testing involved integrating a fleet of five AVs provided by May Mobility into the city's existing public ride-share service—a term referring to rides shared in the same vehicle by two or more different travel parties.

The existing ride-share service that predated the RAPID deployment is provided by Via Transportation within the city limits of Arlington. A maximum of 68 vehicles operate in daily service to provide over 2,000 rides per day as an on-demand microtransit mode on Arlington's existing ride-share service. Figure 3-5 shows the Lexus RX450h hybrid electric vehicles that have been integrated onto the Via service platform, with ADS technology retrofitted into the vehicles by May Mobility to actuate all of the necessary autonomy features—what May Mobility refers to as their "autonomous driving kit."

Figure 3-5. May Mobility deployed Lexus RX450h vehicles augmented by their ADS technology.

Source: City of Arlington, Texas

RAPID's on-demand AV car service vehicles have been continuously operating since March 2021 in partnership with the city of Arlington and the University of Texas at Arlington. Four Lexus hybrids form the essential part of the continuously operating fleet, each carrying up to three passengers with a safety attendant also on board (see the May Mobility vehicle characteristics in Table 3-1). The on-demand car service is operated by May Mobility staff Monday through Friday for 12 hours per day, as funding permits.

One unique aspect of this AV deployment is that the conventional automobiles in the fleet are complemented by another unique vehicle that May Mobility modified from a standard Polaris GEM electric vehicle, specifically to carry one passenger in a wheelchair. Shown in Figure 3-6, this second type of vehicle is operating with the same May Mobility ADS autonomy kit and Via on-demand dispatching service as the Lexus vehicles. This specifically configured, battery-electric vehicle is certified by NHTSA for operation in mixed traffic at speeds up to 25 mph under the FMVSS 500 provisions for low-speed electric vehicles.

The modified design allows a wheelchair ramp to be deployed to the side of the vehicle from the passenger compartment, operated by the safety attendant. The vehicle is designed with wheelchair securement devices and space sufficient to carry one passenger in a wheelchair. This special GEM vehicle design has been deployed by May Mobility at several previous demonstration sites. As part of the RAPID on-demand services, it provides a ready vehicle for dispatching from May Mobility's base of operations whenever a passenger requests wheelchair-accessible service for their ride.

Figure 3-6. May Mobility's Polaris GEM AV shuttle for wheelchair-accessible service.

Source: City of Arlington

The RAPID service area for the AV fleet covers about 1 square mile of city streets around the University of Texas at Arlington and downtown Arlington. Figure 3-7 shows the boundaries of the RAPID service area, which is internal to the larger VIA ride-share service area that spans the entire city of Arlington. For passenger trips contained within the RAPID service area, the user can choose between the RAPID AV service or the conventional ride-share vans.

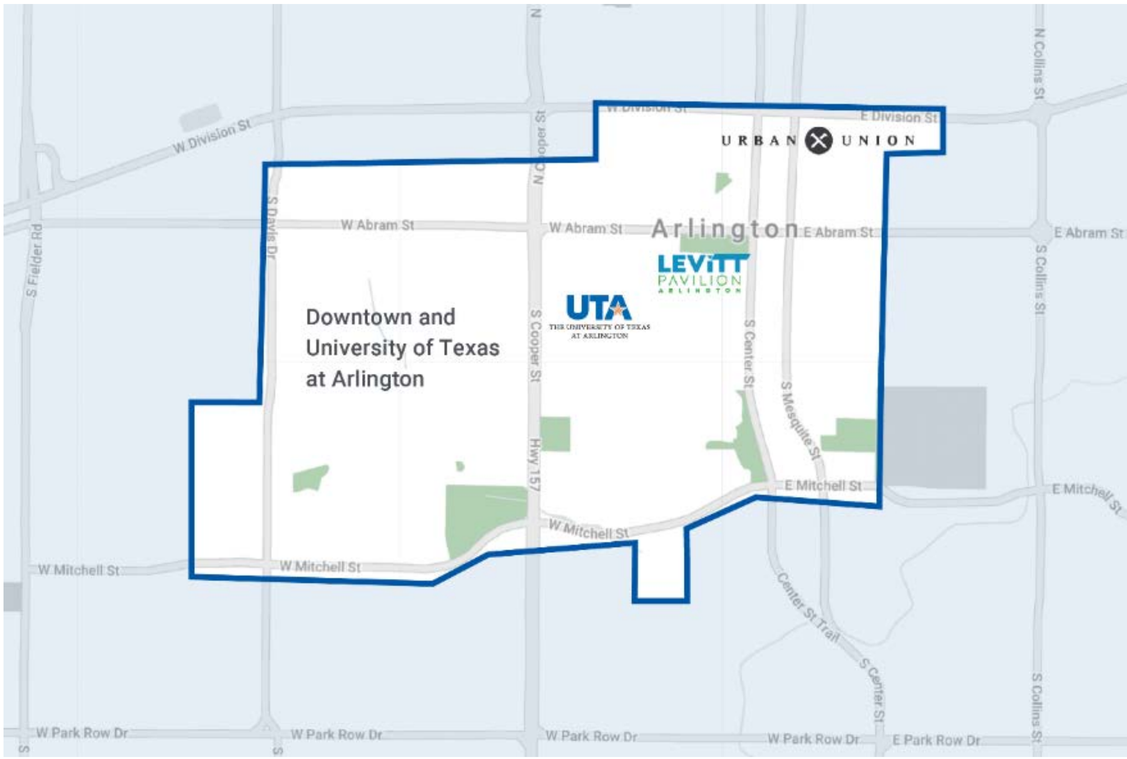


Figure 3-7. Arlington RAPID service area with on-demand AV car services.

Source: City of Arlington

RAPID users can initiate their “on-demand” trip between their origin and destination using the existing Via app that is accessible on their smartphone. The total service area is displayed, but a specific route map for RAPID service with its programmed stopping points is not displayed for public use. Instead, the mobile app provides directions to the nearest point within the service area where the passenger can walk to meet the vehicle dispatched for their specific use—typically no more than one or two blocks away from their current location.

RAPID also provides a customer representative to book rides via normal phone service if the passenger does not have use of a smartphone. Since July 2021, when restrictions from the pandemic adequately subsided, shared rides on RAPID have been permitted, with 70% of passenger trips now being shared, on average.

Figure 3-8 illustrates the “geo-network” on which the RAPID vehicles are programmed to operate and the specific points of service for designated vehicle stops. These are the locations programmed into the AV’s route map where passengers can board and alight, and thus designate the points of trip origin and destination for the RAPID service. However, in keeping with the on-demand nature of the broader Via ride-share service, the user app does not illustrate this “geo-network” of specific stopping locations for the service; rather, the app provides passengers instructions on how to reach a nearby point where they can meet their assigned vehicle.

Maximum operating speed of the AV fleet vehicles when driving in autonomous, self-driving mode is 22 mph. The service network comprises roads that are typical for a low- to moderate-density urban environment, but in areas that have a high level of pedestrian activity. In total, there are 18.4 lane-miles of programmed roadways on which the AV on-demand service operates, and there are 36 programmed stopping locations.

May Mobility operates a local operations control center that continuously monitors the status of all five RAPID vehicles in the AV fleet and provides support to the onboard safety attendants. However, vehicle dispatching is initiated by Via, with specific vehicle trip assignments communicated to the May Mobility vehicles directly through the Via driver app.

Figure 3-8. Primary locations with designated curbfront locations for RAPID service.

Source: City of Arlington

3.2.1 Challenges Faced and Lessons Learned

Arlington's approach to AV testing has always been a phased research approach, with the first AV shuttle deployment being off-street, the second on city streets, and the third on city streets integrated with existing public transportation. Over the 4-year time span of this deployment phase, the city has learned a great deal about the applications and limitations of autonomous technology, the appropriate use cases given the current state of AV technology development, and the insight necessary to evaluate AV developer capabilities overall. Arlington has found that technological advances can occur quickly, and companies can disappear just as quickly. Throughout their research endeavors, the city has focused on two main goals—testing current technology in real-world settings and educating citizens about AV technology. With this approach to testing and education, the city is on target to advance AV utility and acceptance in the future as a continuing form of public transit service.

A few of the challenges faced and lessons learned are summarized below.

Phased Research Endeavors with Technology Startup Firms – The initial project that deployed a fixed-route AV ride-share service in Arlington was in the Entertainment District between 2017 and 2018. This demonstration project proved successful using low-speed shuttle technology designed specifically for this special use. When operating along a fixed route in an ODD without other traffic operating in conflict with the AV shuttles, but with pedestrian activity present along the route, the Arlington project received a special "Box 7" variance from NHTSA that allowed the noncompliant vehicles to be imported from France for limited test and demonstration purposes. The use case operated the vehicles in time-concentrated periods before and after sporting events, with the service connecting passengers between remote parking areas and the sports venues. This limited schedule was adequate for operation within the battery capacity of the electrified vehicles.

The brief second-phase pilot project moved the AV service onto city streets using conventional automotive platforms that were designed to be compliant with NHTSA's Federal Motor Vehicle Safety Standards, and therefore a waiver was not required for the vehicle operations. The vehicles were gasoline-powered, so there were no limitations on daily service times as with the battery-electric low-speed shuttles. However, the vehicles were not conducive to achieving environmental sustainability goals that are commonly sought using electric propulsion vehicles.

The third project phase that operated over the past year under the FTA grant moved the service into a concentrated area where origin/destination trip ends are commonly contained. This was an important step to advance the AV application to autonomous operation of hybrid electric automobiles that do not require battery charging during the service day. As described above, the original vehicle platform that May Mobility developed for prior projects[13] is an NHTSA-approved low-speed vehicle manufactured by Polaris, which was also used specifically for its wheelchair-accessible features to supplement the conventional vehicle RAPID fleet.

This progression of service applications and vehicle technologies has provided the city of Arlington a unique overview of essentially all the AV industry's offerings to public agencies by AV technology new-start firms.

New Operational Phase Approved for Funding – The North Central Texas Council of Governments has approved new funding to extend and enhance the Arlington RAPID AV deployment for an additional 2-year demonstration program likely beginning in late 2022. This fourth phase of the Arlington AV deployments has an objective of moving the technology toward the future point when Level 4 operations do not require safety attendants to travel on board the vehicle with the passengers. Project partners, including the city of Arlington, May Mobility, Via, and University of Texas at Arlington, are contributing funds to keep the service operational, albeit with reduced service hours, in the interim between FTA and North Central Texas Council of Governments funding sources.

The North Central Texas Council of Governments funding allows continuation of the current operations, combined with development, testing, and deployment of a new vehicle platform—the Toyota Sienna Autono-MaaS hybrid minivan. This vehicle platform, shown in Figure 3-9, will also be equipped with the May Mobility autonomous driving kit, and the vehicles will be operated under contract with May Mobility. The extension of RAPID service will also continue

[13] Refer to the description of Site #1: Columbus from the first edition (https://www.nrel.gov/docs/fy20osti/76551.pdf).

to be facilitated by the Via Transportation dispatching system and its associated passenger ride-request mobile app.

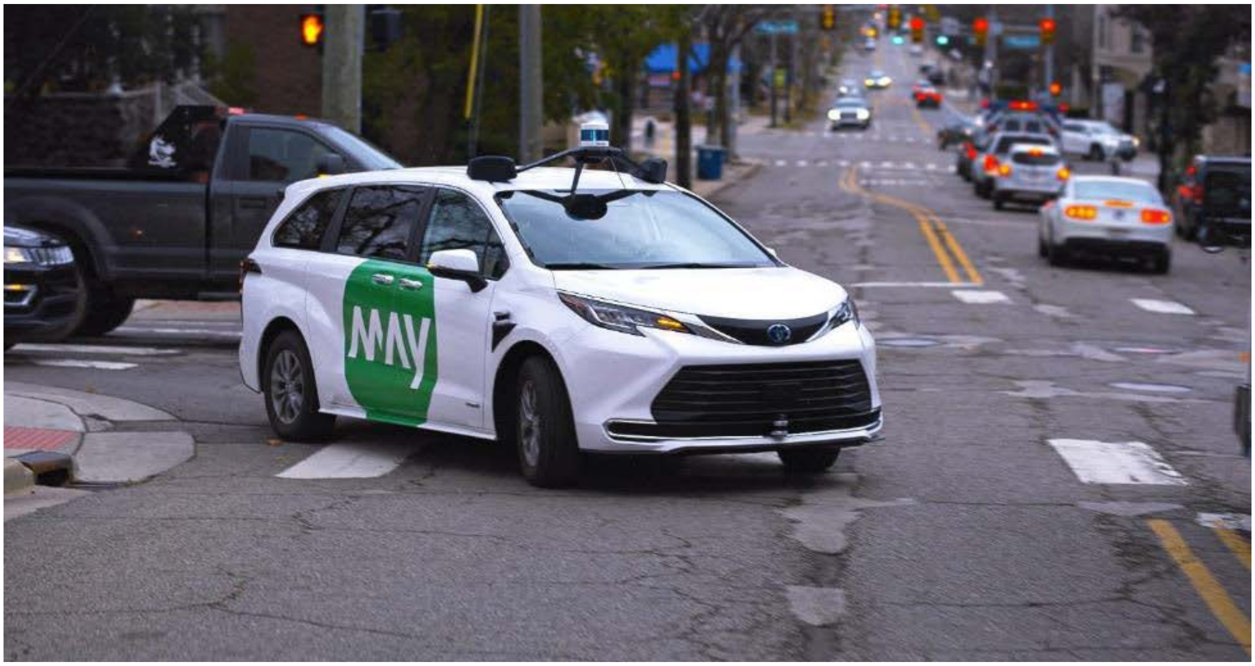


Figure 3-9. The Toyota Sienna MaaS vehicle will be equipped with the May Mobility ADS, using Via's fleet dispatching system to provide point-to-point, dynamically pooled rides.

Source: May Mobility

ODD Limitations for the Most Complex Operating Conditions – May Mobility's AV fleet service that is currently being provided through the RAPID on-demand program can operate at a maximum speed of 22 mph along the geo-network roadways that have been mapped for the service area's ODD. This service has vehicle boarding and alighting locations that are limited to the vehicle stopping locations contained within the programmed route map. Within the boundaries of the route map, autonomous operations are fully integrated into the mixed-traffic roadway operating environment.

However, in the current ODD, certain driving maneuvers are not permitted. This includes unprotected left turns across other traffic movements and certain other movements of similar complexity. For these specific maneuvers, the vehicle is switched to a manual operating mode so that the onboard safety attendant can assume control for a few seconds, as necessary, to complete the maneuver. The resolution of the current limitations of the ODD remains the primary objective of the next development stage by May Mobility. They are developing software that is described as using "multi-policy decision making" to create a unique artificial intelligence. The approach is described as using simulation-based "imagination" in real time to anticipate how surrounding agents could react to different actions of other agents. This is distinguished by May Mobility as being different from an "if/then" set of rules with its ability to "imagine" every possible scenario in just milliseconds of processing time.

New Toyota Sienna Autono-MaaS Vehicle Platform – The new vehicle platform that is being prepared by May Mobility as part of the next phase of RAPID deployment has already had initial testing underway in cooperation with Toyota. This vehicle platform is the result of a strategy to develop mobility-oriented vehicle products that Toyota first announced in 2019.[14] Key features of the special model of the Sienna hybrid minivan include a special interior seating configuration that is designed to accommodate ride-sharing with easy entry and exit of the passenger compartment. Equally important is that the project will include an ADA-compliant Autono-MaaS design built in partnership with Braunability that will contain the equipment necessary to deploy a ramp from the rear of the vehicle by which a passenger in a wheelchair can be loaded. Other features of this new entry into the autonomous AV market are described in Table 3-1, with a comparison to the two other vehicle platforms currently operating in RAPID service. The Sienna is designed to be compliant with the FMVSS rules, with eight airbags for passenger protection during a collision and Toyota's Safety Sense 2 technology for collision avoidance by emergency braking.

3.2.2 Reports and Reference Documents/Websites

The May Mobility website provides a summary of their Arlington RAPID deployment under the webpage designation of "Deployments." The May Mobility webpage describing their deployment in Arlington can be accessed at: https://maymobility.com/deployments/.

Other information on the RAPID on-demand services can be found on the City of Arlington website:

1. City of Arlington. 2022. "RAPID On-Demand AV Car Services for the City of Arlington." Accessed March 28, 2022. https://www.arlingtontx.gov/city_hall/departments/office_of_strategic_initiatives/rapid.
2. City of Arlington. 2022. "VIA On-Demand Rideshare services for the City of Arlington." Accessed March 28, 2022. https://www.arlingtontx.gov/city_hall/departments/office_of_strategic_initiatives/transportation_planning/Arlington_Via_Rideshare.
3. University of Texas at Arlington researchers are performing several different analyses on various aspects of RAPID ridership. They are quantitatively analyzing the monthly ridership data and collecting perspectives of AV riders and non-riders through two surveys. The short survey is sent out to the RAPID riders after each ride and asks about their experience using AVs. The survey tools provide a dashboard for this short survey, which shows the real-time results of the survey. Sampling of the questions and the distribution of the RAPID user responses are accessible through the following link:

   University of Texas at Arlington. 2022. "RAPID Short Survey – Dashboard." Accessed March 28, 2022. https://www.questionpro.com/sd/?t=5XKZcfSSrkeaKHu2RDFBfJ0QJx7V3v6M77Vhd6gMKqPsX1iDHWhaDOyvmCAoayTjLr/JOSlJSfLUwyCEHac8Ug%3D%3D.

[14] Toyota Motor Corporation. 2019. "Toyota's Connected & MaaS Strategy." Feb. 6, 2019. https://global.toyota/pages/global_toyota/ir/financial-results/2019_3q_competitiveness_en.pdf.

Table 3-1. May Mobility Autonomous Vehicle Characteristics – Deployment Site #2: Arlington, Texas.
Page 1 of 2

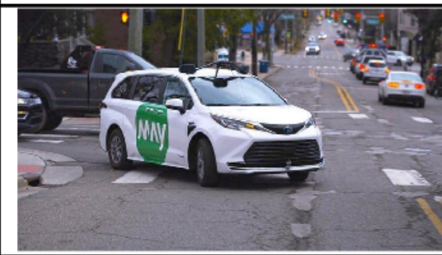
	Vehicle Brand and Model Equipped with May Mobility Autonomous Driving Kit		
Feature/Characteristic/ Parameter	**Polaris GEM - Modified**	**Lexus RX450**	**Toyota Sienna MaaS**
			
Vehicle Classification	**Low Speed Electric Vehicle**	**Sports Utility Vehicle - All Wheel Drive**	**Minivan -- Ride-Hailing Service Model**
A. Passenger Capacity	1 Wheelchair	3	4 to 5 Passengers + 1 Wheelchair Passenger
B. Safety Attendant	1	1	1
C. Vehicle Tare Weight (lbs)	1,696	2,200	4800
D. Vehicle Dimensions (ft.)			
Length (ft.)	13.9	16.0	17.2
Width (ft.)	4.6	6.2	7.6
Height (ft.)	6.1	5.6	6.6
E. Electric Propulsion	Battery-Electric	Hybrid-Electric	Hybrid Electric
Motor Type	VVVF Motor Conttroller	AC Synchronous motor	
Front Drive Horse-Power Rating	N/A	165 hp	AC Induction Moter
Rear Drive Horse-Power Rating	AC Inductiion Motor	175 hp	N/A
F. Maximum Sustained Speed			
Autonomous Operations (mph)	25	25	35
Veh. Max. Speed Capability (mph)	35	112	Information Not Available
G. Typical In-Service Time (hrs)	On-Demand Dispatch for Wheelchair Passenger	2-hour Safety Attendant Shift a) Veh. log & raw data data uploaded in depot	2-hour Safety Attendant Shift a) Veh. log & raw data data uploaded in depot

Table 3-1. Page 2 of 2

Feature/Characteristic/	Vehicle Brand and Model Equipped with May Mobility Autonomous Driving Kit		
	MM Polaris GEM - Modified	**MM Lexus RX450**	**MM Toyota Sienna MaaS**
I. Sensor Array Types	5x Lidar, 7x Cameras, 5x Radar	5x Lidar, 7x Cameras, 5x Radar	5x Lidar, 7x Cameras, 5x Radar
Lidar	1. 4x Ouster OS1 (front, L, R, back)	1. 4x Ouster OS1 (front, L, R, back)	1. 4x Ouster OS1 (front, L, R, back)
	a) Data used up to 60m	a) Data used up to 60m	a) Data used up to 60m
	2. 1x Velodyne VLS-128	2. 1x Velodyne VLS-128	2. 1x Velodyne VLS-128
	a) Data used up to 100m	a) Data used up to 100m	a) Data used up to 100m
Cameras	7x GigE Camera (3x top, 2x side, 1x back, 1x front bumper)	7x GigE Camera (3x top, 2x side, 1x back, 1x front bumper)	7x GigE Camera (3x top, 2x side, 1x back, 1x front bumper)
	a) Data used up to 200m	a) Data used up to 200m	a) Data used up to 200m
Radar	5x Radar (4 corners, front bumper)	5x Radar (4 corners, front bumper)	5x Radar (4 corners, front bumper)
	a) Data used up to 80m -- **see footnote 1.** -	a) Data used up to 80m -- **see footnote 1.** -	a) Data used up to 80m -- **see footnote 1.** -
J. Localization	GPS	1. Fiber-Optic KVH IMU	1. IMU -- Inertial Measurement Unit
		2. GPS	2. Multi-band GPS
		3. Localization using onboard Velodyne Lidar VLS-128 and pre-made HD localization map.	3. Localization using onboard Velodyne Lidar VLS-128 and pre-made HD localization map.
K. Communications/V2I	4G Cellular Onboard Unit	Dual bonded 4G connection -- Primarily for diagnostic data transmissions.	Dual bonded 4G connection -- Primarily for diagnostic data transmissions.
L. Traffic Signal Phase Detection	Camera-based traffic signal phase detection at roadway RSU locations	Camera-based traffic signal phase detection onboard vehicle	Camera-based traffic signal phase detection onboard vehicle
M. Other Comfort Features of Passenger Cabin Design	HVAC - Onboard diesel heating unit	HVAC passenger-cabin climate control	1. HVAC passenger-cabin climate control.
			2. Open cabin design with no front passnger seat.
			3. Power sliding doors -- ease of entry and exit.
			4. Passenger compartment WiFi hotspot.
			5. USB charging ports in the passenger compartment.
N. Special Disabled Passnger Features	1. Vehicle side-deployment of 30 inch wide wheelchair ramp (activated by satey attendant) with a 98 inch long ramp extention to reach a 6 inch high curb-level with a 9 degree slope when deployed to the ground	Not Applicable	1. Vehicle rear-deployment of 32.5 inch wide wheelchair ramp (activated by safety attendant) with a 44 inch long ramp extention to reach street-level with a 13 degree slope.
			2. ADA compliant 4-point wheelchair securement system.
			3. Audio chimes at key ride moments.
			4. Shared overhead rider display.

Footnotes:

1. Radars have maximum range in specific lobes that for the corner radars, are focused up front looking down side streets, and behind looking up vehicle's lane and the adjacent lanes.

3.3 Site #3: Las Vegas – Medical District AV Transit Circulator, Phase 2

During the final phase of the Fremont District AV transit circulator demonstration pilot described in the first edition, the jurisdictional lead for AV deployment shifted from the city of Las Vegas to the Regional Transportation Commission of Southern Nevada (RTC). RTC was in a supporting role during the original pilot project, and it has taken the lead for the next phase that is popularly called the "GoMed" program.

RTC is unique among the transportation jurisdictional authorities within the United States in that it has the combined authority over not only public transit services, but also the roadway system traffic management and the downtown Las Vegas shared bike services. RTC also serves as the designated metropolitan planning organization by coordinating the long-range planning for all transportation agencies in southern Nevada.

The GoMed project is the popular name for RTC's $8.2-million Medical District Automated Circulator and Connected Pedestrian Safety Program. RTC was awarded a $5.3-million Better Utilizing Investments to Leverage Development (BUILD) grant from FTA in 2018, with a federal cost share of 65%. The city of Las Vegas is a supporting partner for project development and implementation.

The objective of the project is to deploy four AV transit vehicles to serve the vulnerable populations that must access the district's key facilities and vital services, including elderly residents and persons with disabilities. The route will connect the Bonneville Transit Center in downtown with Medical Center destinations that include not only the hospitals and medical offices providing a full range of health care, but also locations providing access to educational facilities. The ridership will comprise patients and their visitors, as well as students and employees on their daily transit commute.

The project entails several elements of technology application, as depicted in Figure 3-10. Of primary importance will be the features enhancing the safety for elderly pedestrians and those with mobility challenges. These technology application features are all managed from the RTC operations center. This combination of technology applications satisfies RTC's focus on enhancing mobility at a multimodal level.

The first element of the project is connected AVs operating along the route and communicating with the project's second new technology application in the form of 20 roadside units. These roadside units will also be communicating data to another 300 connected vehicles operating within the Medical District service area, including RTC buses, RTC and city of Las Vegas fleet vehicles, and emergency vehicles.

Twenty-three Smart Transit Shelters are the third element of the technology application deployed over 21 locations. General market shelters will be retrofitted with digital displays to provide real-time transit information and other smart technologies (e.g., smart efficient lighting, security cameras, passenger presence detection) to increase the safety and enhance the experience of transit users. Nine of the 21 Smart Transit Shelter locations are designated as GoMed AV transit stops.

The project will be leasing four electric AVs that meet FTA's grant requirements, including Buy America, the FMVSS, and FTA's ADA regulations. Release of the RFP for lease of the AVs and the operations and maintenance of the GoMed service is planned in the early summer of 2022.

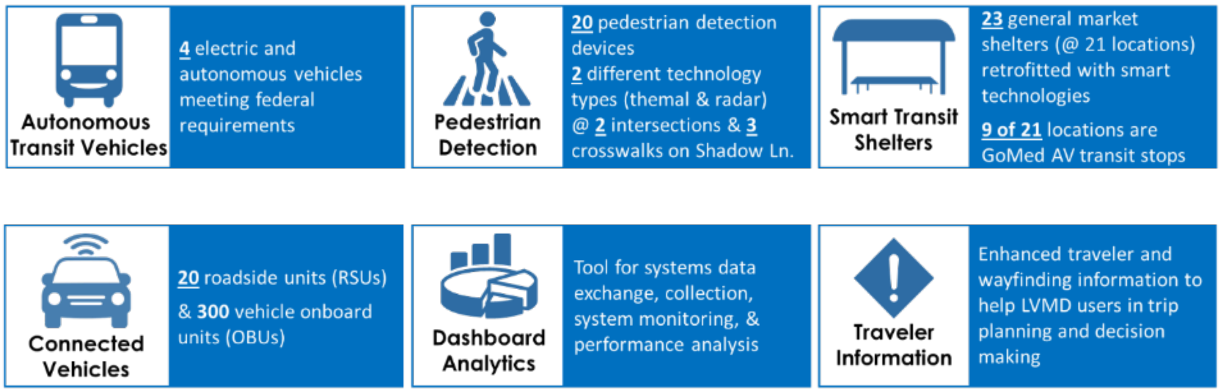


Figure 3-10. GoMed project's six advanced technology applications.

Source: RTC

The project will also deploy two different types of pedestrian detection technology (20 devices) at five locations, detecting the additional time needed for pedestrians in crosswalks to complete crossing at traffic intersections and extending green signal phase for safety when needed, or initiating flashing beacons at the uncontrolled crosswalks.

Communications through the connected vehicle technology application involves the roadside units transmitting traffic signal phase and timing data, as well as speed limit and pedestrian safety alerts to the autonomous vehicles and other connected vehicles equipped with onboard units.

A fifth technology application called Dashboard Analytics will establish a central data hub. The Dashboard Analytics platform will interface, process, and exchange data with all the various project technology applications. The dashboard will also monitor the system and provide analytics to assess the system performance in real time.

Enhanced traveler and wayfinding information is the final area of advanced technology being deployed. The existing rideRTC and GoVegas mobile apps will be updated and enhanced to help Medical District users with trip planning and decision-making. Traveler and wayfinding information will also be provided via digital displays installed at the Smart Transit Shelters.

Figure 3-11 shows the planned 3.8-mile-long operating route, with the AV fleet operating on 8-minute headways spanning 9 hours of service each day. Three of the four vehicles are planned to be in service, with the fourth remaining in standby mode while charging in the maintenance and storage location. The vehicles reach a maximum speed of 25 mph, with an anticipated average travel speed over the length of the route of 15 mph, including station dwells.

With respect to the project schedule, project design has been completed, and construction and system deployment begins in fall 2022. The AV testing and commissioning and overall system acceptance testing is planned for mid-2023, followed by the launch of the GoMed transit services in automated operation during fall 2023.

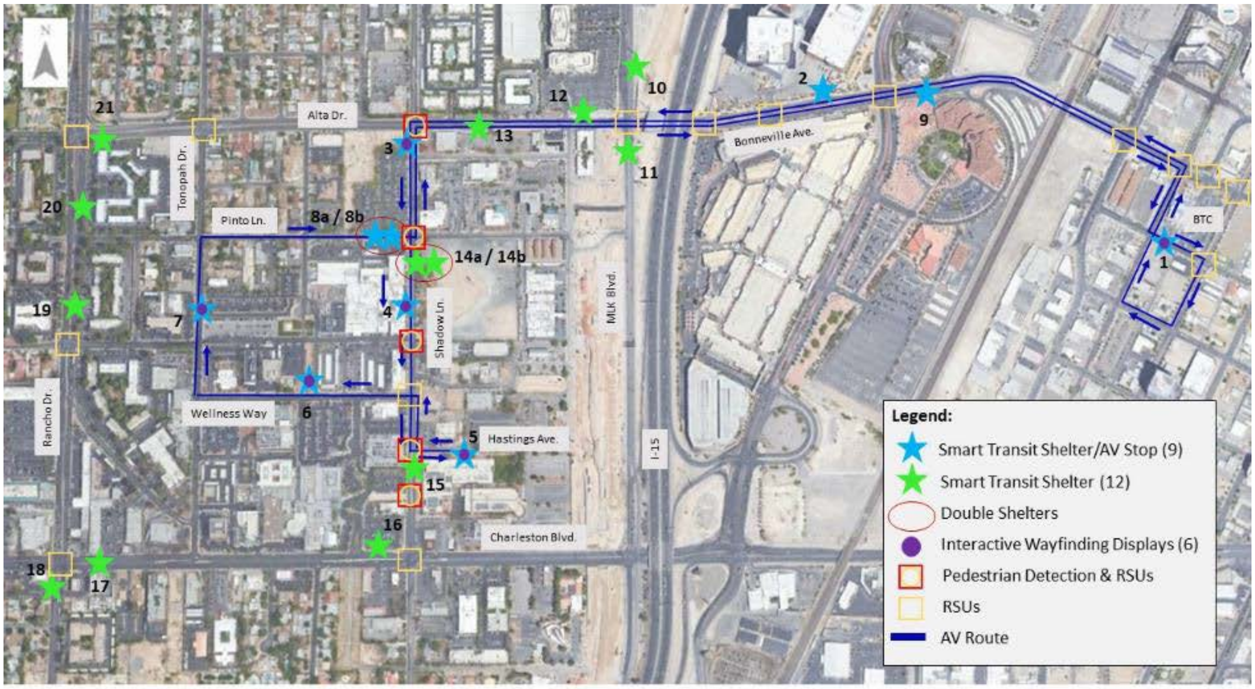


Figure 3-11. GoMed AV circulator travel route, Smart Transit Shelter, pedestrian detection, and connected vehicle roadside unit locations.

Source: RTC

3.3.1 Challenges Faced and Lessons Learned

RTC is looking beyond the early demonstrations of low-speed AV shuttles that were deployed during the initial pilot in 2018–2019 to new AV technologies that meet the funding requirements for the GoMed project. As noted above, these grant requirements include a Buy America provision, which most of the AV shuttle suppliers did not satisfy in their prior demonstration pilot deployments.

Secondly, meeting FMVSS results in wholly different vehicle platforms from the low-speed AV shuttle that was deployed in the Fremont District circulator. At the time of writing this document, this requirement was expected to result in responses to the RFP using more conventional vehicles that have been equipped with an autonomous ADS kit and the associated sensor stack as opposed to custom-designed AVs. However, the prospect of a vehicle without a steering wheel, brake pedals, or rearview mirrors is now possible in light of NHTSA's early indications of allowing selective exemptions for limited numbers of vehicles without such features.

The single most daunting requirement of the funding grant stipulations for the GoMed project was the full compliance with FTA's ADA requirements. This alone may determine (or have the greatest impact) on the type of vehicle platform that is ultimately selected for deployment on the project.

The lessons learned by RTC from these early AV initiatives, when combined with the FTA grant stipulations and its transportation planning responsibilities as the metropolitan planning organization for southern Nevada, have prompted RTC to closely monitor several other AV deployments occurring in Las Vegas. These include AV deployments now being initiated by Motional/Via and Lyft along the Las Vegas Strip, where many casinos are concentrated. In addition, the Las Vegas Convention and Visitors Authority is planning to connect the Las Vegas downtown and convention center facilities with the Las Vegas Strip by expanding the Boring Company system now operating in manual mode at the convention center.

3.3.2 Reports and Reference Documents/Websites

As of the writing of this document, the GoMed project was pending the release of the RFP for the AV technology, and no reports on the project have been issued.

3.4 Site #4: Jacksonville Transportation Authority Ultimate Urban Circulator Project – First Implementation Phase

The Jacksonville Transportation Authority (JTA) is moving ahead with their multiphase project called the Ultimate Urban Circulator (U^2C). JTA has made major strides in the deployment of what is described as their "journey to build the first autonomous vehicle transit system in the United States."[15] At the time of the 2020 publication of the first edition of the *AMD Implementation Catalog*, JTA was in a preliminary phase now referred to as the "Test and Learn" program. The first full implementation (Phase 1) has now been initiated, which will deploy the AVs in transit service. Beginning with an RFP in 2021, the process has progressed to the selection of a design team that will design and guide the procurement of the Phase 1 project and oversee its operation along the Bay Street Innovation Corridor (BSIC).

These initial project phases provide the foundation for the subsequent and transformative Phase 2 implementation. The Phase 2 implementation will retrofit the existing dual-lane structures of the bidirectional, 2.5-mile Skyway Express to allow AV shuttle vehicle technology to operate along the aerial transitway's entire length. The elevated transitway structures were built in the 1980s and 1990s as part of the Downtown Automated People Mover program funded by the U.S. Department of Transportation.

Figure 3-12 shows the original large automated people mover vehicle technology that began operating in 1989 along the three-station segment between the convention center and downtown. This infrastructure, which resembles a U-shaped viaduct roadway configuration, was originally designed to support the larger vehicle shown in the 1989 photograph. This original vehicle was a 100-passenger vehicle manufactured by Alstom for the French aerospace firm Matra—the system supplier for the original starter-line phase. The Matra-Alstom vehicle was a conventional large automated people mover class of vehicle technology.

This larger vehicle technology did not continue operation after the first extension was built extending the system throughout downtown Jacksonville. JTA replaced the large vehicles in 1996 with the current small monorail system, which has continued operation throughout the last

[15] JTA's CEO Nathanial Ford stated this ideal objective in his introductory comments to the JTA webinar on the U^2C program, sponsored by COMTO on November 18, 2021. The virtual webinar was titled "Reimagining the Future with Autonomous Vehicles: How the Ultimate Urban Circulator Creates Connections, Opportunities and Community," and the primary presentation was given by Mr. Bernard Schmidt, JTA's Vice President of Automation.

25 years. However, the design of the heavier U-shaped guideway structures and the associated stations was retained when JTA constructed the subsequent expansions of the Skyway system.

The importance of the continued utilization of the original infrastructure cannot be underestimated, since the transitway infrastructure that was originally designed for large vehicles will be returned to a similar form and function when the Skyway is retrofitted with medium-sized AV shuttle vehicles, as depicted in Figure 3-13.

Figure 3-12. Original Phase 1A segment showing 1989 automated people mover technology (left), and the retrofitted small monorail beam currently in place today (right).

Source: J. Sam Lott, Automated Mobility Services, LLC (left); Google Earth (right)

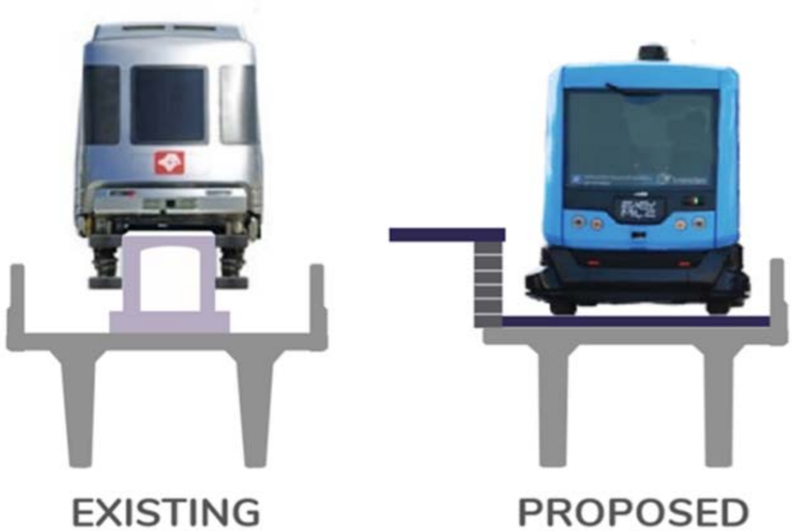


Figure 3-13. Concept for removing the monorail beam to return the structure to rubber-tired automated vehicle technology similar to the original vehicle form factor.

Source: JTA

Another key feature of the Phase 2 work is shown in Figure 3-14. Phase 2 will include a transition from the Phase 1 Bay Street Innovation at-grade street alignment to the Phase 2 retrofitted aerial transitway. This will allow vehicles operating throughout the Phase 1 segment to then access the Phase 2 aerial alignment and stations within the Downtown and South Downtown districts.

Figure 3-14. Phase 2 transition to grade to allow U²C vehicles to operate along the BSIC AV lanes.

Source: JTA

The plan to operate vehicles both at grade and on the aerial transitways is at the heart of the U²C concept. Figure 3-15 depicts how the Phase 1 Bay Street alignment will be interconnected with the Phase 2 Skyway alignment with a vertical transition (ramp), allowing the two systems to converge at the east end of the Innovation Corridor.

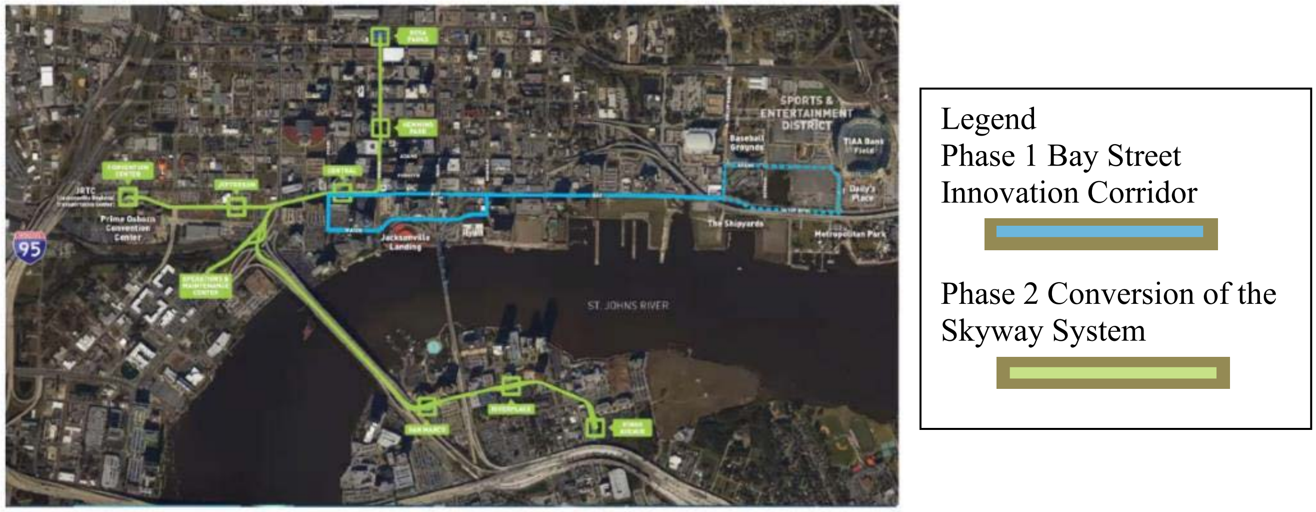


Figure 3-15. Combined Phase 1 Bay Street Innovation Corridor and Phase 2 conversion of the existing Skyway system to allow AV technology to operate throughout the larger system.

Source: JTA

The U^{2}C project has evolved to an 8-year implementation program, with the current project timeline found in Table 3-2. The progress to date, combined with the schedule for the planned successive implementation phases, demark important achievements for the emerging AV transit industry.

Table 3-2. Historical and Planned Timeline for the Complete U^{2}C Program

2015–2016	Initial approvals for U^{2}C given by the JTA boards.
2018–2019	JTA awarded the Better Utilizing Investments to Leverage Development (BUILD) grant to fund the preliminary phase, initiating one-third-mile test track demonstration of multiple AV technologies near the Sports Complex.
2020	Driverless operation by unmanned AV shuttles carrying COVID-19 test samples to the laboratory within Mayo Clinic campus.
2021	Phase 1 Bay Street Innovation Corridor RFP awarded.
2023	Bay Street Innovation Corridor project will launch, and the Phase 2 planning, development, and engineering tasks are engaged.
2025	Phase 2 Skyway conversion to the U^{2}C begins.

AV shuttles will begin operation on the BSIC by 2023. Phase 2 planning and engineering will also begin in 2023, preparing for public-private partnership discussion with interested parties through industry forums over the following few years. Contract award proceeding to constructing the Skyway conversion project is targeted to begin in 2025.

The final Phase 3 deployment will create vertical transitions (ramps) from the aerial alignment to at-grade alignment at multiple locations. This will allow at-grade street operations to extend the U^{2}C service into the surrounding neighborhoods and activity centers. Figure 3-16 shows this ultimate U^{2}C buildout plan.

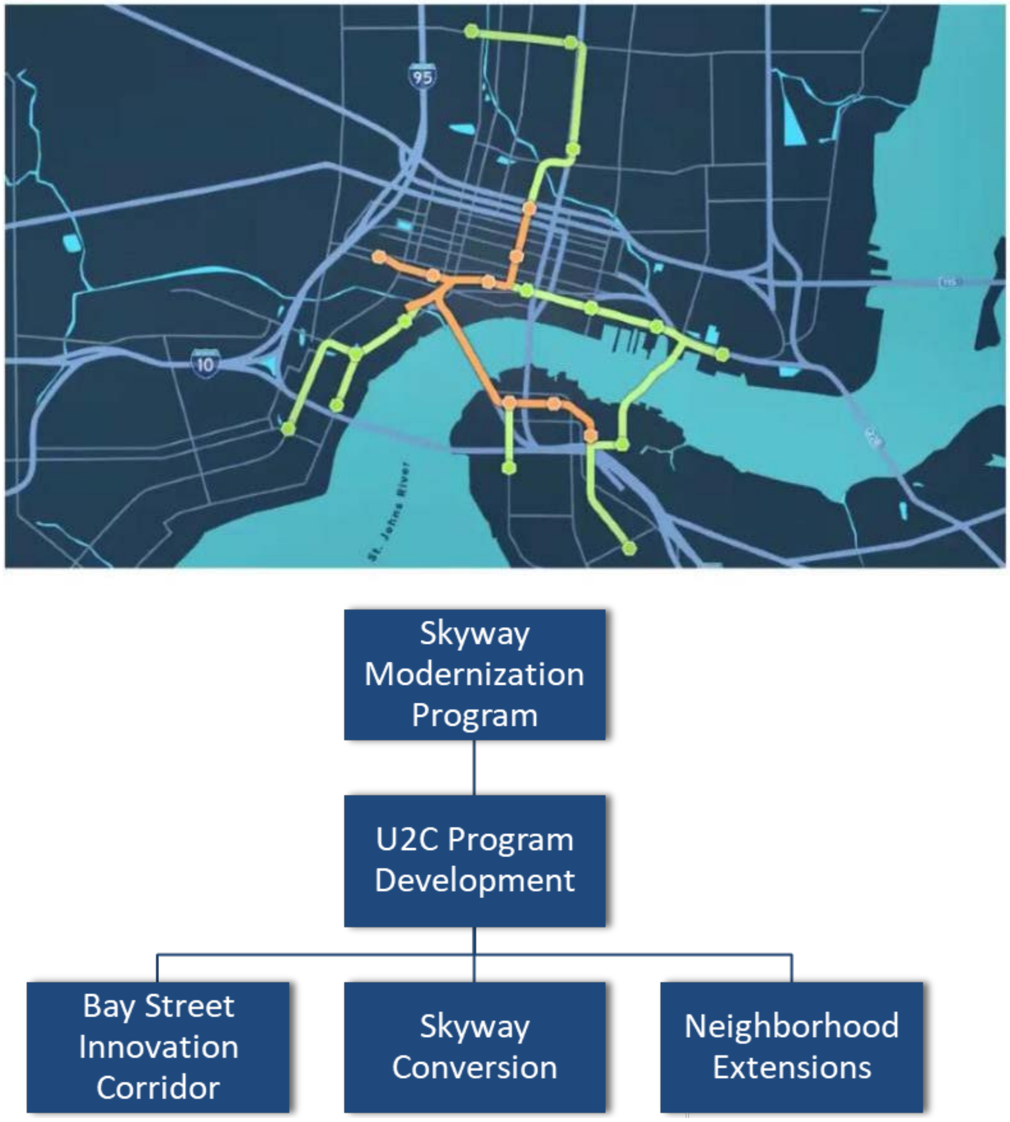


Figure 3-16. Phase 3 ultimate U^{2}C adds 10 miles of additional AV service to reach adjacent neighborhoods and activity centers.

Source: JTA

3.4.1 Challenges Faces and Lessons Learned

The “Test and Learn” preliminary phase has remained active since 2018. Even during the height of the COVID-19 pandemic, JTA teamed with Beep to operate a Navya vehicle shuttling COVID test samples across the campus at the Mayo Clinic to the lab for processing. This special vehicle deployment was accomplished with Level 4 driverless vehicle operation.

The first edition of the AMD catalog reported on the earliest stage of Test and Learn, which was a one-third-mile test site comprising a dedicated lane between two stations within the sports complex surrounding the Jacksonville Jaguars football stadium. In this earlier test program, different AV developers were invited to bring a vehicle to operate as part of the demonstration pilot. During 2021, the testing program was relocated to two dedicated test facilities. One of the test facilities' detailed test procedures have been developed, as shown in Table 3-3.

Table 3-3. Sample Test and Learn JTA Test Procedures

Test Procedure: ADS-2	Perform a lane change/low-speed merge
Test Procedure: ADS-3	Move out of travel lane to pull over/park
Test Procedure: ADS-5	Detect and respond to static signs
Test Procedure: ADS-7	Perform vehicle following
Test Procedure: ADS-9	Detect and respond to bicycles
Test Procedure: ADS-12	Detect and respond to emergency vehicles
Test Procedure: ADS-13	Detect and respond to object in the travel lane
Test Procedure: ADS-14	Sensor performance in low lighting condition/weather-induced low visibility

Each test procedure is defined within a document containing test objectives, methods, and associated protocols to be followed. Testing of vehicles continues at the Armsdale Test and Learn Facility, including the Navya and Perrone EV Star paratransit vehicles. The facility is capable of both outdoor and indoor operations. This test facility is shown in Figure 3-17.

Figure 3-17. Vehicle testing at the Armsdale Test and Learn Facility.

Source: JTA

Test and Learn Facilities – A test facility at the Florida State College of Jacksonville Cenil Center campus was added to the Test and Learn program. This facility adds the capability to test battery charging equipment and study implications of battery charging cycles on continuous transit services.

Vehicle-to-roadway infrastructure communications equipment, including both onboard units and roadside units, are being tested to assess how this can increase the AV shuttle's safe operation in mixed-traffic conditions with pedestrians. Detection of pedestrians crossing the vehicle path and communication of that condition to the vehicle is one of the specific areas of testing currently underway at the facility. Also in test is the communication of traffic signal phase and timing to alert the AV in advance of the actual signal change.

One of the benefits from the Test and Learn program has been the development of design requirements for the use of multiple sensor types to adapt to changing weather conditions. Lidar, with its high spatial accuracy, is typically the primary sensing system, with other types of sensors providing secondary sensing capability. However, testing at the Florida State College of Jacksonville revealed that lidar has significant problems when operating in rain. As a result, JTA is considering a design requirement to switch between primary and secondary sensing systems when necessary to continue safe vehicle operations.

Programmatic Approach to Research and Development – A strength of JTA's U^{2}C project is the coordination and direct linking of AV testing with the future phase planning and design efforts. Table 3-4 lists the objectives, milestones, and tasks/initiatives that JTA has advanced over the past several years. This will come to full fruition in the implementation of the Phase 1 BSIC project.

Table 3-4. U^{2}C Programmatic Objectives and Milestones

Objectives and Milestones	Related Tasks and Initiatives
Establish criteria, standards, and test objectives	• Leverage past Test and Learn data and experience • Develop initial guidance document known as "Golden 20" to AV industry
Test AV shuttles and other AV technologies	• Build direct relationships with AV manufacturers and technology companies • Assist AV and tech companies with their NHTSA strategies • Develop an independent NHTSA strategy for the BSIC
Establish AV requirements for AV transit	• IT/cybersecurity • Concept of operations plan • Risk mitigation
Consult with public safety, legal, and insurance stakeholders	• Incorporate feedback from first responders and BSIC council (local) • Interaction with legal community • Relationship with insurance companies
Release for procurement of vehicles	• RFP preparation under BSIC work plan

JTA has engaged with a number of AV suppliers and technology firms to share data and information. Some of these suppliers have been invited to participate during the Test and Learn process. The range of firms that JTA has engaged in industry discussions include:

- Navya
- Ohmio (HMI Technologies)
- Local Motors
- Perrone
- Major vehicle manufacturers
- 2getthere
- EZ Mile
- Beep
- Lilee.

In total, seven vehicles have been tested thus far by JTA. JTA asserts that the final selection will not be biased or influenced by these initial tests. They plan to move forward toward a formal procurement process to be initiated during the Phase 1 BSIC project. Mr. Bernard Schmidt, VP of Automation, stated during his November 2021 presentation for the Conference of Minority Transportation Officials (COMTO) national webinar that JTA was investigating a range of vehicle options, supporting technologies, and their associated risks and cybersecurity vulnerabilities. In the final implementation, JTA would like to be able to operate a range of vehicle sizes from different manufacturers, all with interoperability on the U^2C system.

<u>Phase 1 BSIC Design Activities</u> – In the initial deployment, there will be a measured increase in complexity of the operating environment beyond the testing that has already been accomplished. AV shuttle technology will be deployed primarily in a dedicated lane operating throughout the BSIC Phase 1 project, with limited operation in mixed-traffic conditions at some points along the alignment. Operations will be a fixed-route transit service between four dedicated BSIC passenger stations.

Phase 1 design will also address the initial design studies and development of the Phase 2 retrofit of the Skyway aerial transitway system to accommodate the selected Phase 1 AV shuttle technology. JTA's intent for this comprehensive multiphase design effort and its related AV shuttle system technology procurement is to develop suitable requirements and specifications that support a complete and integrated AV transit system. The design team selected from the 2021 RFP is led by Balfour Beatty.[16]

A key design element is the fleet management plan encompassing the Phase 1 and Phase 2 system, and its associated remote command and control center. From this control center, vehicle operations will be monitored and controlled by operations personnel at both a system level and at the individual vehicle level. A stated objective by JTA is that the command and control center can remotely operate a vehicle in the event that a vehicle is stopped due to a situation outside its capabilities or outside the vehicle's ODD. For example, if another vehicle is blocking the travel

[16] Metro Magazine. 2021. "JTA Taps Balfour Beatty V2R Team for Bay Street Innovation Corridor Project." Aug. 28, 2021. https://www.metro-magazine.com/10150201/jta-taps-balfour-beatty-v2r-team-for-bay-street-innovation-corridor-project?utm_source=website&utm_medium=contentoffers&utm_campaign=092221.

lane preventing an AV from proceeding, remote personnel can remotely steer the vehicle to recover operation without dispatching personnel to the scene. In concept, when the stopped AV shuttle generates an alarm at the control center, personnel can remotely pilot the vehicle from the operations center to steer around the blockage, after which it would then be returned to its automatic operating mode.

The JTA Golden 20 – A direct work product resulting from the Test and Learn preliminary phase is a specific list of key criteria and technology/operational objectives. This document has been shared with JTA's industry group participants and will continue to serve as the top-level guideline for the Phase 1 BSIC project implementation. These "Golden 20" are listed in Table 3-5. In a June 2019 transmittal memo to AV manufacturers and tech companies, Bernard Schmidt, VP of Automation, referred to the Golden 20 as identifying the *"critical requirements for acceptable deployment of Autonomous Vehicle Shuttles for the Ultimate Urban Circulator (U^2C) program. These requirements are particular to the JTA but are analogous to what we believe are critical requirements for all public transit agencies looking to deploy such a service."* The memo added that this list was their initial guidance, and that it could be modified going forward.

Table 3-5. JTA's Golden 20 – Critical Needs of Autonomous Shuttles/Vehicles Source: JTA

1	Full ADA compliance
2	Buy America/Buy American compliance
3	Cybersecurity
4	Remote route programming with low latency
5	NHTSA approval to operate on public roads
6	Vehicle-to-infrastructure and vehicle-to-everything capabilities (dedicated short-range communications [DSRC] and 5G)
7	Traverse slope of 12 degrees with full passenger load (sustained acceleration/deceleration)
8	Operate bidirectionally up to 35 mph
9	12+ hours of battery life
10	Operate at speeds of 15 mph within 1+ feet of a stationary object; operate at speeds of 15 mph within 3+ feet of a moving object
11	May operate during inclement weather (rain, fog, wind, and extreme heat)
12	Internal cab – environmental control with rapid cool capability and sustained temperature with full passenger load
13	Ability to be towed, push/pull, and steer AV manually or towed via another AV
14	Crashworthy up to 35 mph
15	Ability for fast-charge opportunity charging
16	Ability to regulate passenger capacity
17	System for recording/storing video for at least 30 days (black box)
18	Emergency button to contact authority agency control center
19	Remote command and control operation of vehicles with low latency
20	Complete vehicle monitoring system, including health monitoring

The Golden 20 indicate the initial requirements that will guide the planning and design of the Phase 1 BSIC and Phase 2 retrofit design of the Skyway system. The retrofit includes replacing the existing monorail automated people mover technology with the ultimate U^2C AV shuttle fleet and its operational supervisory control system. These requirements also have design implications for the retrofit of the station facilities to accommodate the new vehicle technology.

Known JTA Challenges and Essential Criteria – In the November 2021 webinar, Mr. Schmidt concluded his remarks by listing the known challenges and related criteria/issues that need to be addressed by JTA and the industry. He indicated that in order to move forward with full implementation of Level 4 automated vehicle technology while operating in public transit service, the following challenges need to be adequately addressed:

- **Legislation and Policy** – These need to be addressed both at the federal and state levels.
- **Safety Standards** – Although the prevailing standard now is the FMVSS, JTA proposes that an “AVSS” safety standard specific to AV technology be developed, possibly through the American Public Transportation Association.
- **Public Involvement** – Comments during the webinar Q&A session noted that JTA has engaged the public for input on accessibility by those who are disabled, as well as with the Bay Street Innovation Council of stakeholders/agencies. Further, a first responder council is active, providing input to JTA during the Test and Learn program.
- **AV Automobiles vs. AV Shuttles** – Reference was made to the EV Star paratransit bus that was converted to an AV using the Perrone automated driving system equipment. There was also reference in the webinar to the prospect of deploying a “purpose-built” vehicle that meets all of the JTA requirements and fits the form, fit, and function ultimately determined necessary for the Phase 2 deployment.
- **Workforce** – JTA believes that this technology will be a job creator for the transit industry, and they are working with the Florida State College at Jacksonville to develop an AV-oriented curriculum for educating and training this new workforce. As part of this program, Florida State College at Jacksonville has opened their own 1-mile-long test facility to test the operation of AV technology on their campus.
- **Technology Cost** – It was noted in Mr. Schmidt’s remarks that the cost trends for deploying AV technology is downward, indicating that over time the JTA projects are expected to bear those benefits.
- **Technology Maturation** – During the Q&A session, weather impact “edge cases” that render some sensing technologies ineffective were discussed, such as the effect of heavy rain on lidar systems. JTA’s investigation into this phenomenon during their testing program, and the resulting mitigation requirements improving reliability by switching the priority of the sensing systems (see discussion above) during those weather events, was one example of this maturation process.
- **Electric Vehicle Infrastructure** – The challenge of creating suitable EV charging infrastructure is inherent in the Golden 20 requirements for a 12-hour battery life while in continuous transit service. This challenge goes beyond equipping the maintenance depot with EV charging stations. Strategic placement of EV fast-charge infrastructure along the route or at stations is needed to provide “opportunity charging” (#15) as a vehicle is in active passenger service.

3.4.2 Reports and Reference Documents/Websites

The following sources provide further information about the U^{2}C program and the people leading this initiative:

- COMTO National. 2022. "Reimagining the Future with Autonomous Vehicles: How the Ultimate Urban Circulator Creates Connections, Opportunities and Community." COMTO National and Jacksonville Transportation Authority webinar, Nov. 18, 2021. Accessed April 22, 2022. https://comtonational.org/event/jta-and-comto-webinar-reimagining-the-future-with-autonomous-vehicles/.
- Descant, Skip. 2021. "AV Transit Projects are Progressing to Full-Scale Deployments." *Government Technology*, June 9, 2021. https://www.govtech.com/fs/av-transit-projects-are-evolving-to-full-scale-deployments.
- JTA. 2021. "JTA Awarded $1.72 Million RAISE Grant for U^{2}C." Press release, Nov. 19, 2021. https://www.jtafla.com/media-center/press-releases/jta-awarded-1-72-million-raise-grant-for-u2c/.

3.5 Site #5: Houston, Texas – University District AV Transit Circulator, Phase 2 Demonstration

For the University District Phase 2 project, Houston METRO is implementing this new phase with funding provided through an FTA Accelerating Innovative Mobility (AIM) grant. Programmatic aspects of the transition to the next phase of development and deployment, as well as the necessary grant award and the partnerships for funding and contracting, were discussed in Section 2.1.

A Phoenix Motorcar Zeus 400 battery-electric paratransit shuttle bus, as shown in Figure 3-18, will be equipped with an automated driving system kit from a suitable supplier selected by an RFP process. Known at the Zeus 400 Shuttle Bus, the vehicle is built on a Ford E450 Superduty chassis, outfitted with a Starcraft Allstar paratransit vehicle body that also is fitted with a wheelchair lift. These two aspects of the vehicle make it compliant with FMVSS, as well as the Federal Transit Administration's ADA access regulations for this class of transit vehicle.

The Zeus 400 vehicle is assembled here in the United States by Phoenix Motorcars, and thus satisfies Buy America guidelines. Vehicles of this specific design have logged over 2.3 million zero-emission miles in a variety of use applications. Up to 24 seated passengers can be accommodated, depending on the mix of wheelchair and seated passengers on board at any time.

Figure 3-18. University District AV circulator Phase 2 R&D vehicle – Phoenix Motorcars Z400 electric shuttle

The University District Phase 2 route is moving from a pedestrian walkway on the university campus to city streets, connecting from the TSU campus to the U of H main campus approximately 0.5 miles away. This shuttle will functionally provide a first-mile/last-mile transit connection to METRO's Purple Line LRT system from TSU to the TDECU Stadium station adjacent to the U of H football facility, which can be seen in Figure 3-19. This connection will also accomplish a societal objective of allowing residents of a historic public housing project adjacent to the TSU campus to reach the LRT station as well.

The maximum operating speed of the AV shuttle during the Phase 2 deployment is being restricted to 15 mph, and the associated legal speed limits for all traffic along the route has been determined by the city of Houston to be restricted to 25 mph. Some maneuvers like unprotected left turns across oncoming vehicles can only be made by the onboard "safety attendant" taking control of the vehicle. For that reason, the route is being carefully considered to limit or eliminate these turning conditions, referred to as the "geo-net" approach to route planning previously discussed in Section 2.2 as a common means of simplifying mixed-traffic operating conditions.

The intersection identified with a yellow circle on the route map in Figure 3-19 is one location where the AV route would cross the LRT tracks on one possible route alignment, as well as pass through a major arterial street's signalized intersection at a main entrance to the U of H remote parking facilities. Also within the yellow circle is the LRT station, around which a high level of pedestrian activity occurs throughout the day.

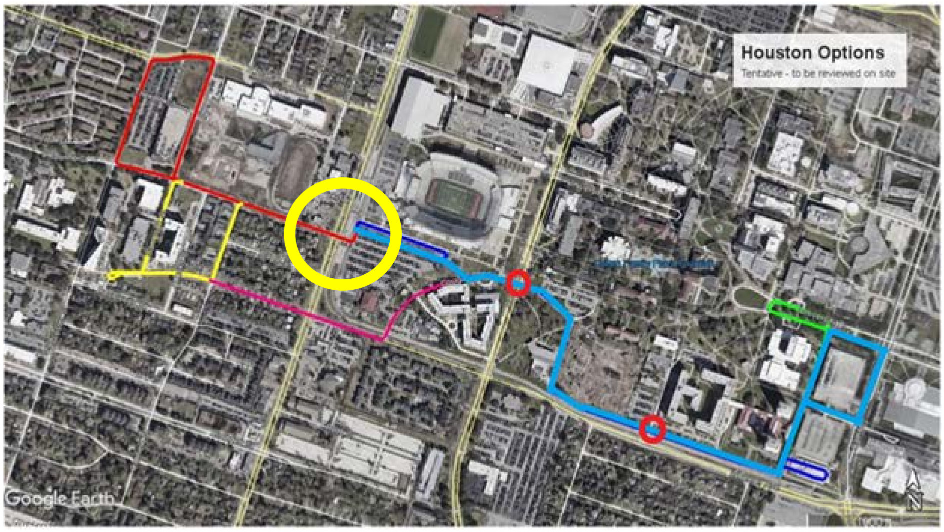


Figure 3-19. University District AV circulator Phase 2 route options

The complexity of this roadway intersection's operations makes the route choices more challenging and raises the importance of a comprehensive assessment of a control system design that incorporates an LRT signaling system interface. Also required would be transit signal priority feature in the roadway's traffic signal controls, and the potential for adding advanced traffic control infrastructure technology that is communicating with the AV shuttle bus throughout the approach to the intersection

This key intersection will require significant new infrastructure to communicate with the vehicle on its approach and passage through the intersection. Such intelligent roadway infrastructure implementation will facilitate CDA capabilities and is consistent with the authors' assertion that research and development in CDA is necessary and critical in preparation for deploying large-scale AV transport systems.

These matters of route operational complexities, vehicle-to-infrastructure communications, and cooperative driving automation are critically important aspects for METRO's selection of the ADS supplier for the Phase 2 project.

3.5.1 Challenges Faced and Lessons Learned

After the past few years of AV project planning, procurement, and implementation throughout several phases of AV shuttle deployment, the following list of challenges and lessons learned have been prepared by Houston METRO for consideration of others wanting to pursue similar projects:

- **Contract Negotiations** – No existing template for a novel project of vehicle service as a software project currently exists. Staff learning curve on autonomous vehicle deployment, operations, risk assessments, and insurance is steep. The lessons learned include:
    - Conduct an industry forum prior to procurement.
    - Have a clear, concise business case geared toward your agency and/or customers' needs.

- **Contract Execution** – Extended time is required for contract execution due to new provisions, new technology, insurance requirements, and third-party contract acceptance. The associated lessons learned are:
    - Research peer agencies with similar projects.
    - Begin conversations with third parties as early as possible.
- **Agency Acceptance** – Staff education of technology and service is required. Lessons for similar project consideration are:
    - Share industry literature with internal stakeholders to minimize the new technology learning curve.
    - Research, share, and encourage staff to attend webinars in their respective areas related to the project.
- **Creating Scope** – When creating the project scope, be sure to collaborate with your agency's offices for operations, safety, maintenance, IT, and innovation, as well as any third-party stakeholders. The lessons applicable to future projects are:
    - Set up an internal coordination team to flesh out issues and develop resolutions as needed.
- **External Partnerships** – Project partners need to understand cost share and realistic timelines. This can be addressed in the earliest stage of the project through:
    - Establishing regular working meetings among the project partner agencies.
    - Establishing memorandums of understanding (MOUs) or other such agreements so roles and expectations are clearly defined.
- **Turnkey Services** – Defining "turnkey services" within the project and what's required from the vendor/operator is a significant challenge. Lessons to be applied are:
    - Clarify in detail the roles and responsibilities of each party, but build in flexibility where possible, since new challenges will emerge as the project progresses.
    - Some flexibility in contractual definitions of the services is key.
- **Project Communication Plan** – Keeping all project stakeholders informed and performing their part of the work in a well-coordinated team effort is challenging when a number of agencies and entities are involved. An important lesson is:
    - Create in the earliest stage of work a project communication plan that provides for weekly or biweekly meetings with project stakeholders for project updates and to coordinate project logistics and ensure that the project timeline remains on schedule.
- **Project Budget/Contingency Reserve** – Determining the indirect costs that may be associated with the project can be difficult. The lesson is:
    - Reserve at least 10% of project budget for unexpected project costs.

- **Project Supervision on Third-Party Stakeholder Site** – The planning and execution of project tasks is problematic if the project manager, operations supervisor, or vendor management is not located on-site. The lesson learned is:
    - When project is located on third-party site, ensure that there is adequate oversight from the operations team supervisor/management level.
- **Definition of Deliverables and Corresponding Project Execution** – The conduct of adequate discussion of the roles and responsibilities of the project managers to execute project scope requires proper attention. The lessons that address this challenge are:
    - Identify a project manager or point of contact at any third-party-controlled site.
    - Ensure adequate coordination between the on-site project manager and agency.
- **Schedule of Deliverables/Task Completion** – Using previously defined goals, create an action item list to deliver and meet project goals, metrics, or key performance indicators. The lesson to be applied is:
    - Ensure all stakeholders have input into the schedule and plan their internal resources accordingly.
- **Data Management Plan** – Increasing the visibility and impact of data collection from different stakeholders who are tracking and contributing data to the project requires a focused approach by creating a data management plan. The lesson is:
    - Establish a data collection template as part of the planning phase of the project to ensure data collected is consistent across all parties.
- **Emergency Response Plan** – Creating an emergency response plan to address environmental threats and campus threats is important to accomplish before operations begin. This preparation must include local police and safety officers responsible for the deployment site and transit agency safety personnel, as well as obtaining the vendor emergency response plan (if available). The lesson learned from this challenge is:
    - Create an operational plan that includes operations personnel from all parties/stakeholders, local municipalities, third-party site officials, and local law enforcement officers.
- **Maintenance Schedule** – The challenge when the deployment project lacks a suitable maintenance schedule is that system operations will be unnecessarily disrupted. The lessons on how to mitigate this situation are:
    - Create or obtain a maintenance schedule for the AV shuttle to address preventative shuttle repairs and vehicle modifications from design and/or software updates with the least impact on scheduled operations.
    - Retain a mechanic for performing on-call repairs as needed to ensure continuity of service.
- **Shuttle Delivery** – Understanding the equipment and service needs for delivery from door to door may not be obvious, especially when shipments occur from overseas. The lesson is:

    - Transporting vehicles for local delivery may require agency action (e.g., securing the services of a flatbed truck operator to complete delivery process to the site).
    - See also the above challenge of project supervision on a third-party stakeholder site.
- **Battery Charging Requirements** – Technical requirements for battery charging can be easily miscommunicated to the AV shuttle operator, particularly when a third-party site is the location for the equipment installation, potentially resulting in additional cost to upgrade the power supply and equipment provisions. The lesson learned is:
    - Reserve at least 10% of project budget for unexpected project costs.
- **Travel Lane Infrastructure and Markings** – The sensing technology by which the AV shuttle vehicle determines its proper path and steers itself along the transit lane requires appropriate lane marking and roadway infrastructure. In the case of the Phase 1 deployment, the pavement lane reflectors were not bonded sufficiently to sustain the wear and tear of shuttle operations, pedestrian traffic, and weather. The lesson is:
    - Be prepared to implement alternative and/or multiple roadway lane markings and other "localization" infrastructure required by the vehicle sensing and controls.
- **Public Education** – The role of a public agency in introducing new transportation technology involves public outreach and education. The lessons learned are:
    - Invest in the creation of resources to clearly explain the vehicle, its capacity, and its limitations.
    - Host community days and reach out to local communities to schedule group tours to experience the new technology in operation.
- **NHTSA Regulations** – An unforeseen NHTSA directive to cease all EasyMile EZ10 shuttle operations in passenger service within the United States had a major impact on the Phase 1 AV shuttle demonstration pilot project. The important lesson is:
    - Work closely with the agency's government/legislative affairs team to handle regulatory matters when they occur.
- **Impacts of the COVID-19 Pandemic** – The COVID-19 pandemic resulted in stay-at-home orders and school closures, including the TSU campus site for the Phase 1 demonstration project, which impacted shuttle operations and caused the early termination of the Phase 1 project. The lessons learned are:
    - Develop a plan to order and communicate changes to shuttle operations when contagious illnesses are an active concern.
    - Develop a social distancing plan to implement while sustaining operations (where possible).

3.5.2 Reports and Reference Documents/Websites

A final report was prepared on the University District AV shuttle Phase 1 demonstration pilot that describes the planning and preparations, as well as the operational conditions and associated research of the AV shuttle deployment on the TSU campus. The report was prepared by the TSU

Center for Transportation, Training, and Research, and the funding for the report preparation was provided by the Houston-Galveston Area Council.

The complete report can be accessed on the Houston-Galveston Area Council website through the following links:

- TSU Center for Transportation, Training, and Research. 2020. *Texas Southern University Automated Vehicle: Final Report*. Houston, TX: Houston-Galveston Area Council. https://www.h-gac.com/getmedia/5467d78f-8b9c-4ccf-966f-50228fb35463/TSU-AV-Pilot-Final-Report-October-2020.
- TSU Center for Transportation, Training, and Research. 2020. *Texas Southern University Automated Vehicle: Final Report, Appendix A – Summary of Locations Considered for the AV Storage Locations*. Houston, TX: Houston-Galveston Area Council. https://www.h-gac.com/getmedia/6a8facd9-b2b9-4717-ac69-512f3a077987/Appendix-A-Summary-of-Locations-Considered.
  Several locations on TSU's campus were considered for the storage and charging of the AV shuttle. This appendix provides highlights of the factors identified and the lessons learned.
- TSU Center for Transportation, Training, and Research. 2020. *Texas Southern University Automated Vehicle: Final Report, Appendix B – Houston's University District AV Transit Circulator System Study – Phase 1 Physical Planning and Phase 2 Operational Analysis*. Houston, TX: Houston-Galveston Area Council. https://www.h-gac.com/getmedia/23f63ec9-272c-4607-a17f-e4f87e858f8e/Appendix-B-Phase-1-Physical-Planning.

  Appendix B begins with the background planning and strategic approach to the AV project from initial discussions in 2017. The project was viewed as a University District encompassing both TSU and U of H. Project demonstration funding was provided by the Metropolitan Transit Authority for the TSU Tiger Walk project. This appendix includes early considerations of the University District leading to the TSU Tiger Walk project, then describes elements of the TSU AV project, and ends with a prospectus of future AV implementation using information learned from the TSU demonstration project. This appendix was compiled and originally submitted as a Technical Memorandum II and is a stand-alone report. It is supplemental to the TSU AV demonstration shuttle findings. References to Technical Memorandum II may be seen throughout the report.
- TSU Center for Transportation, Training, and Research. 2020. *Texas Southern University Automated Vehicle: Final Report, Appendix C – Automated Electric Shuttle Data Collection and Analysis*. Houston, TX: Houston-Galveston Area Council. https://www.h-gac.com/getmedia/d9c6e729-7f58-48bf-993a-4d7f6abc15ee/Appendix-C-INL-Presentation.

  Appendix C consists of a presentation from Matt Shirk of Idaho National Laboratory, which included an assessment of TSU's AV battery endurance. The TSU assessment was part of a U.S. Department of Energy initiative that was concurrently conducting such assessments for several U.S. automated vehicle projects. Idaho National Laboratory installed a meter at TSU's Central Storage facility to compile readings when the vehicle recharged and transmit those data to Idaho National Lab to be processed. This presentation provides a background to this effort, describes how the data were collected and assembled, and presents results and findings concerning energy consumption forecasts for future AV transit applications. The research was performed under the auspices of the U.S. Department of Energy Vehicle Technologies Office Systems and Modeling for Accelerated Research in Transportation (SMART) Mobility initiative. Figure 3-20 shows the key findings of the research, with other supporting information found in Appendix C of the TSU shuttle final report.

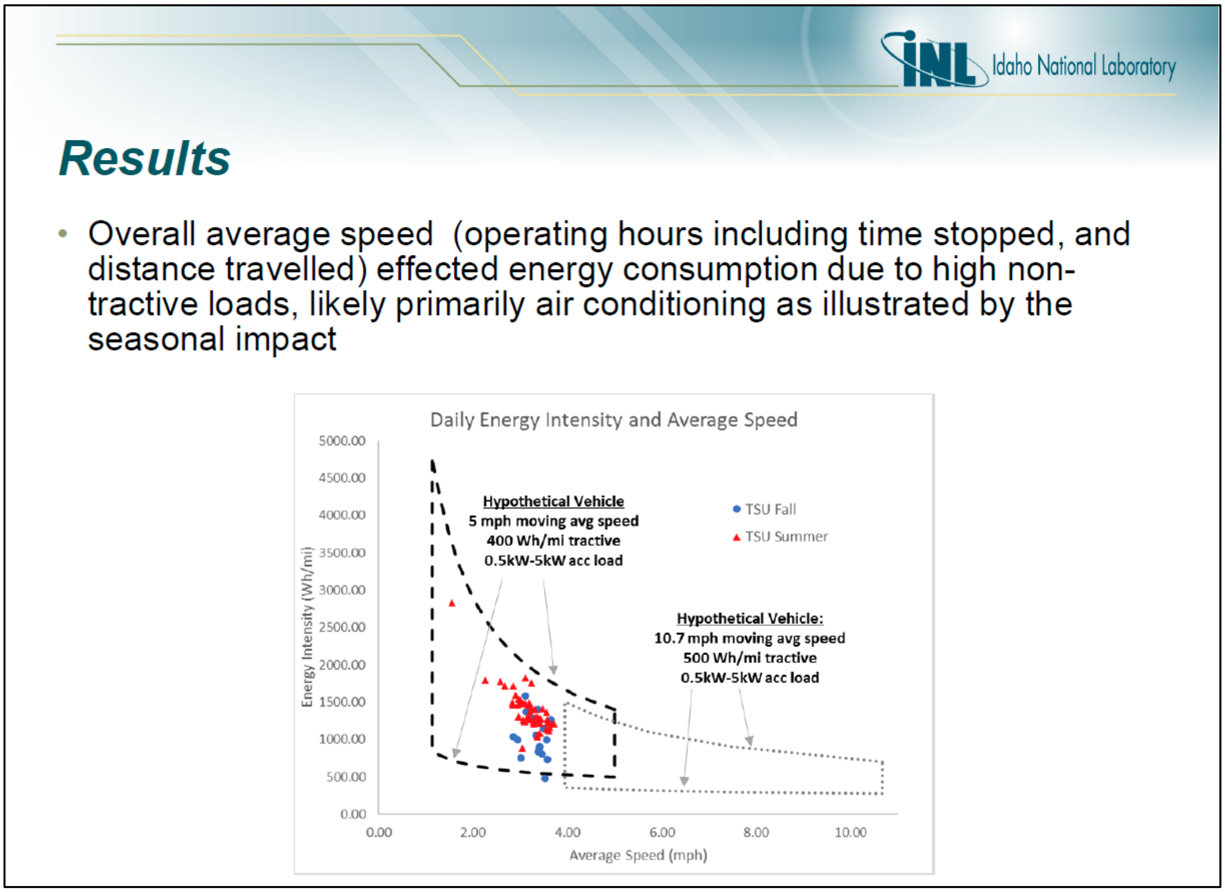


Figure 3-20. Final results of the Idaho National Laboratory energy use data collection for the TSU shuttle operation.

Source: Idaho National Laboratory

The energy use data collected by Idaho National Laboratory during the TSU AV shuttle Phase 1 pilot project were combined with data from similar low-speed AV shuttle deployments at other sites, including the Mcity site deployment (see Section 3.6). These combined data were used to derive composite results, which have been included in a U.S. Department of Energy report.[17]

[17] U.S. Department of Energy Office of Energy Efficiency and Renewable Energy. 2020. *SMART Mobility: Connected and Automated Vehicles Capstone Report*. Washington, D.C.: Office of Energy Efficiency and Renewable Energy. https://www.energy.gov/sites/prod/files/2020/08/f77/SMART-CAVS_Capstone_07.22.20.pdf. Refer to Section 3.1.8, "Use Cases and Energy Characterization of Lower-Speed Automated Shuttle Applications." A version of Figure 3-20 with all of the energy intensity data points from all of the sites that were monitored is found on page 84.

3.6 Site #6: Mcity – Driverless Shuttle Project Conclusion

Mcity at the University of Michigan is a research center exploring many aspects of advanced mobility, including research, testing, and development of connected and automated vehicles and technologies. As such, the deployment of a French company Navya's AV shuttle at Mcity—described in the first edition of the *AMD Implementation Catalog*—was a phase of R&D that progressed to a conclusion as part of a three-phase deployment, known as the Mcity Driverless Shuttle research project. Figure 3-21 is a graphic taken from the final white paper written by Mcity staff to report findings of the research project for two Navya Autonom shuttle vehicles.

Phase One	Phase Two	Phase Three
June 4–Aug. 24, 2018	Nov. 5, 2018–May 24, 2019	Aug. 22–Dec. 13, 2019

Figure 3-21. Phased deployment routes for the Mcity driverless shuttle.

Source: Mcity

The white paper focuses primarily on extensive surveys of shuttle riders and non-riders to gauge consumer acceptance of automated vehicle technology, with a particular focus on the self-driving mode of fixed-route transit demonstrated at the site. Global market research company J.D. Power worked directly with Mcity to develop the survey instrument used during the study. This survey, along with others reflecting related consumer opinions, were referenced in the final report.

The recommendations given in the final white paper (see Section 3.6.2) included the following emphasis for others considering an AV shuttle deployment:

- An automated shuttle service should provide a solution to an existing transportation challenge.
- Offering popular routes and reliable service during peak demand are key to a successful deployment.
- Do not overlook physical attributes of the shuttle itself: speed, seating configuration, and comfort impact the rider experience.

<u>Mcity Partnership in a New AV Deployment</u> – Mcity has partnered with Ann Arbor SPARK, a local economic and business development organization, and the state of Michigan to deploy a new AV shuttle service in Ann Arbor, Michigan, that began operation in October 2021. This new deployment features the operation of a more conventional automobile technology equipped with an automated driving system designed by the AV technology firm May Mobility, a University of

Michigan spinoff based in Ann Arbor, Michigan. May Mobility is also a partner in this project, which is called the A2GO Autonomous Vehicle Shuttle Service, with the vehicle shown in Figure 3-22.

Figure 3-22. A2GO on-demand AV shuttle service in Ann Arbor is operated by May Mobility in partnership with Mcity, the state of Michigan, Ann Arbor SPARK, and others.

Source: Mcity

The free, on-demand service has other participating sponsors, and connects the University of Michigan campus with other areas in Ann Arbor. The service deployed four hybrid Lexus RX 450h vehicles, as well as one Polaris GEM vehicle designed and equipped to accommodate a wheelchair passenger. The service plan is modeled after a similar deployment in Arlington, Texas, called RAPID, which operates as a demand-response service (see the description for this Site #2 in Section 3.2).

More information on the Ann Arbor A2GO service can be found at: https://annarborusa.org/a2go/.

3.6.1 Challenges Faced and Lessons Learned

The Mcity deployment of Navya automated shuttles was one of the first deployments of this new technology on public roads in the United States. The research-oriented environment of Mcity provided an excellent base for researchers, as well as strong organizational support to assess the technology and service, and to develop the findings. Some of these research findings are mentioned in the first edition of the *AMD Implementation Catalog*.

Key Findings of the Mcity Driverless Shuttle Research Project – The final Mcity white paper provides the following key findings of the project's research:

- The Mcity driverless shuttle was the first automated shuttle pilot project in the country focused primarily on consumer research and data collection. The research project ended in 2019, with a safety record free of major incidents. The shuttle, manufactured by Navya, is described in the white paper as Level 4 AV-capable, as defined by SAE. This means it is designed to operate without a human driver on a limited, controlled route. Mcity, in an abundance of caution, employed onboard safety conductors who manually resumed operations after the shuttle automatically stopped at certain intersections, consistent with Level 3 AV capability.
- A successful driverless shuttle service should provide a viable and practical transportation solution that uses automated technology.
- Outreach and education are key to engaging the community and promoting ridership.
- Trust drives consumer interest in automated vehicle technology; 86% of shuttle riders, following their ride, stated they trusted the Mcity driverless shuttle, as did 66% of non-riders.
- The experiences of riders and non-riders with the shuttle positively impacted their thinking about personal self-driving vehicles, generating more interest in the technology.
- Riders and non-riders cited the shuttle's slow speed, 10 mph on average, as a negative factor. Interestingly, the low speed appealed to riders because they perceived the risk was lower, yet it worked against the shuttle as a practical solution to daily transportation challenges. Increasing the speed of travel was the highest-rated improvement solution for both riders and non-riders, followed by improving the route, convenience, and quantity of the stops.

3.6.2 Reports and Reference Documents/Websites

In addition to a previously referenced document from Mcity detailing its shuttle research project, titled *Mcity Driverless Shuttle: A Case Study*, the final concluding documentation for the project has now been released:

- Kolodge, Kristin, Sarah Cicotte, and Huei Peng. 2020. *Mcity Driverless Shuttle: What We Learned About Consumer Acceptance of Automated Vehicles*. Ann Arbor, MI: Mcity. https://mcity.umich.edu/wp-content/uploads/2020/10/mcity-driverless-shuttle-whitepaper.pdf.

In addition to the report issued at the end of the research period, Mcity plans to make the raw data from the deployment available in 2022. Interested parties should contact Mcity directly to gain access to the raw data. Some raw data may be redacted at the discretion of Mcity to provide appropriate protection of personally identifiable information.

3.7 Site #7: Rivium 3.0 – Rivium Business Park and Central District ParkShuttle Circulator

The first edition of the *AMD Implementation Catalog* described the existing AV shuttle system that has operated in the Rivium Business Park since 1999, located in the city of Capelle aan den Ijssel, Netherlands. The current plan is to bring the third-generation vehicle online as part of what is now being called Rivium ParkShuttle 3.0. This third phase of the AV shuttle transit line, described in first edition, primarily involves expansion of the system operations on the south end of the line. This expansion plan has not changed significantly over the last 2 years.

The initial elements of Rivium 3.0 involved the replacement of the second-generation vehicles, which have been in service for about 20 years while operating along the original protected lane alignment. Notably, these older vehicles were operating in Level 4 automation throughout the duration of their service time without any onboard operator. The replacement of the fleet of six vehicles with third-generation vehicles operating on the original route is currently underway as of the writing of this report. Figure 3-23 shows a new vehicle as it operates on the transitway's iconic bridge structure over the A-16 expressway.

Figure 3-23. Third-generation AV ParkShuttle vehicle operating on the single-lane section of the bridge spanning across the expressway.

Source: 2getthere, a company of ZF

The ParkShuttle's dedicated roadway terminates on the north end at the Rotterdam metro station, as seen in Figure 3-24, where it passes underneath the A-16 expressway to reach the rail station. On the south end of the dedicated roadway alignment, an extension to the service will reach the center of the Rivium district. The extension will connect with city streets on which the new generation of AV shuttles will operate in mixed traffic. This aspect of the Rivium 3.0 project is currently in the planning process as of the writing of this document.

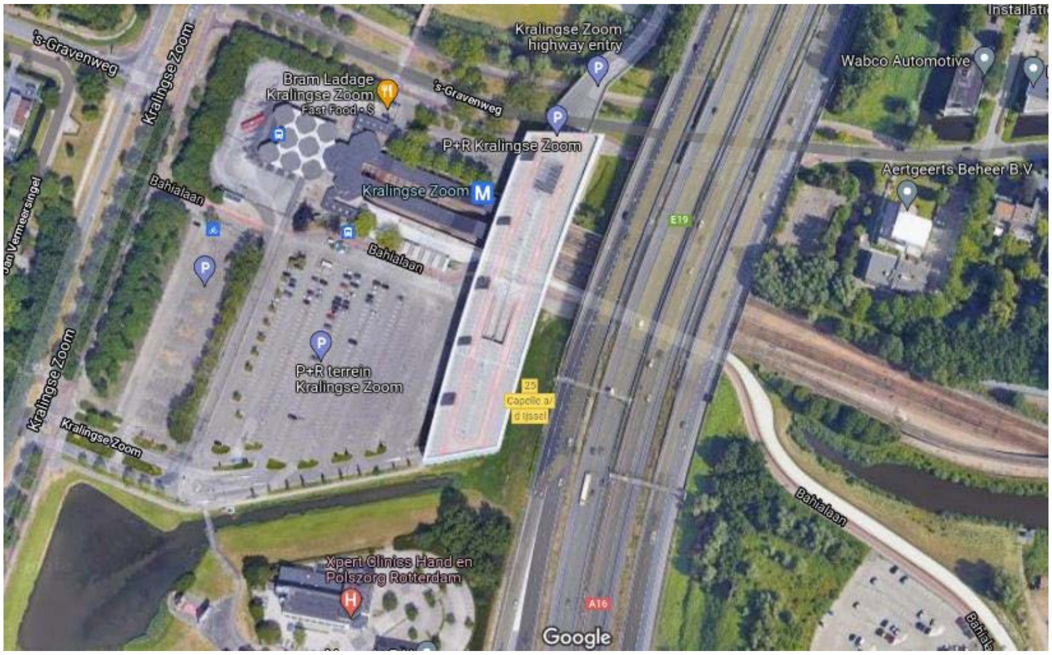


Figure 3-24. ParkShuttle system connection to the Kralingse Zoom rail station of the Rotterdam metro.

Source: Google Earth

An important development at the beginning of 2020 was the acquisition by ZF Group—one of the world's largest automotive equipment suppliers—of a major stake in the Dutch company 2getthere. ZF has since taken full ownership, and 2getthere is now identified as a company of ZF. This acquisition provides 2getthere the resources of a worldwide parent company that is a major force in the automotive industry. ZF has a corporate focus on expanding its product lines in the field of autonomous vehicles overall by providing numerous advanced technology parts and subsystems for automotive manufacturing and assembly. Furthermore, ZF is marketing their "autonomous transport system" as a mobility solution. The press conference video at the 2022 Consumer Electronics Show in Las Vegas in January 2022 underscored this new product line and ZF's emphasis in automation. See the link to this video in Section 3.7.2.

Connexxion—a subsidiary of Transdev—is the system operator of the Rivium ParkShuttle. Connexxion is contracted to operate the system through 2033 by the Rotterdam regional transportation authority. The operations personnel manning the system's control center are Connexxion staff members who use 2getthere's system supervisory control software to manage the operations.

Figure 3-25 shows the complete alignment with extensions that comprise the Phase 3 project, and Figure 3-26 provides a perspective on the project's location relative to the center of Rotterdam. Note that the illustration denotes several segments that are a single lane, such as the bridge over the expressway shown in Figure 3-24. The single-lane segments have the opposing movements of shuttles sequenced (analogous to traffic signal control) through these segments by the AV fleet's automated supervisory control software.

Also shown in Figure 3-25 are the segments on which the AV shuttles will operate in mixed traffic on the south end of the line, extending service to reach the Brienenoord Bridge Waterbus station. This ultimate connection by the ParkShuttle from the Waterbus line to the Rotterdam metro system's Kralingse Zoom rail station, passing through Rivium, will be the third and final phase of the deployment, increasing the daily ridership significantly.

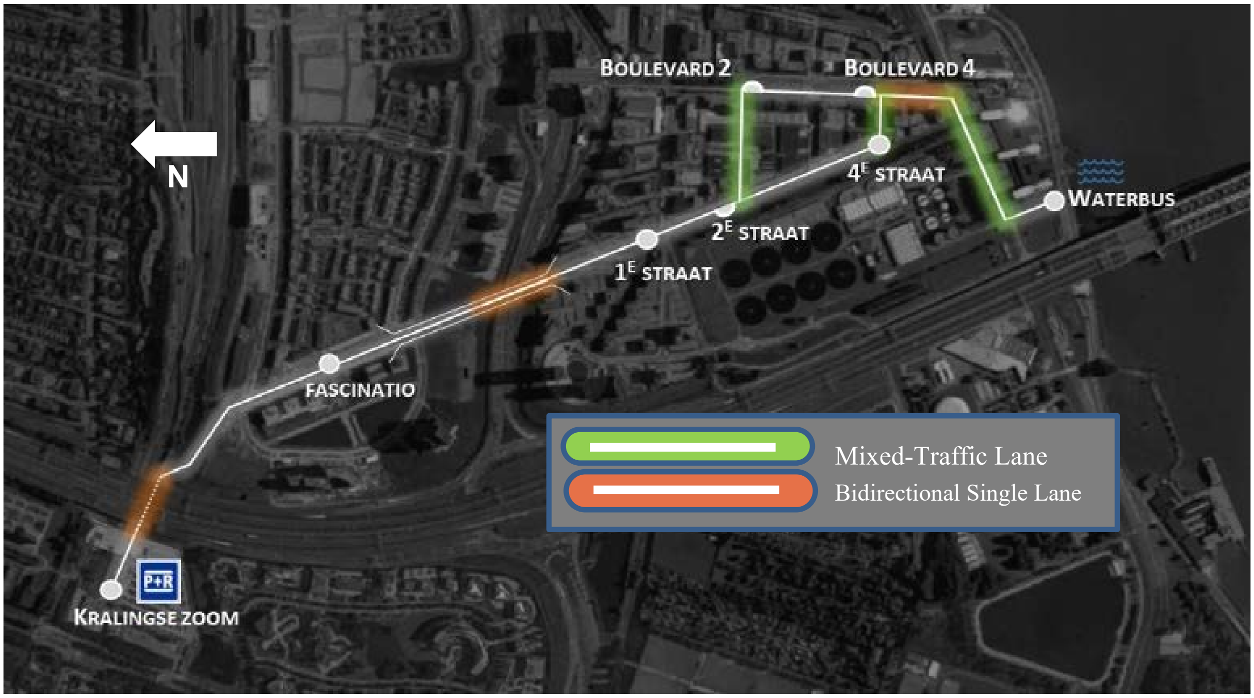


Figure 3-25. Rivium Business Park AV shuttle alignment for the complete Phase 3 expansion, with mixed-traffic segments and single-lane segments shown.

Source: 2getthere, a company of ZF

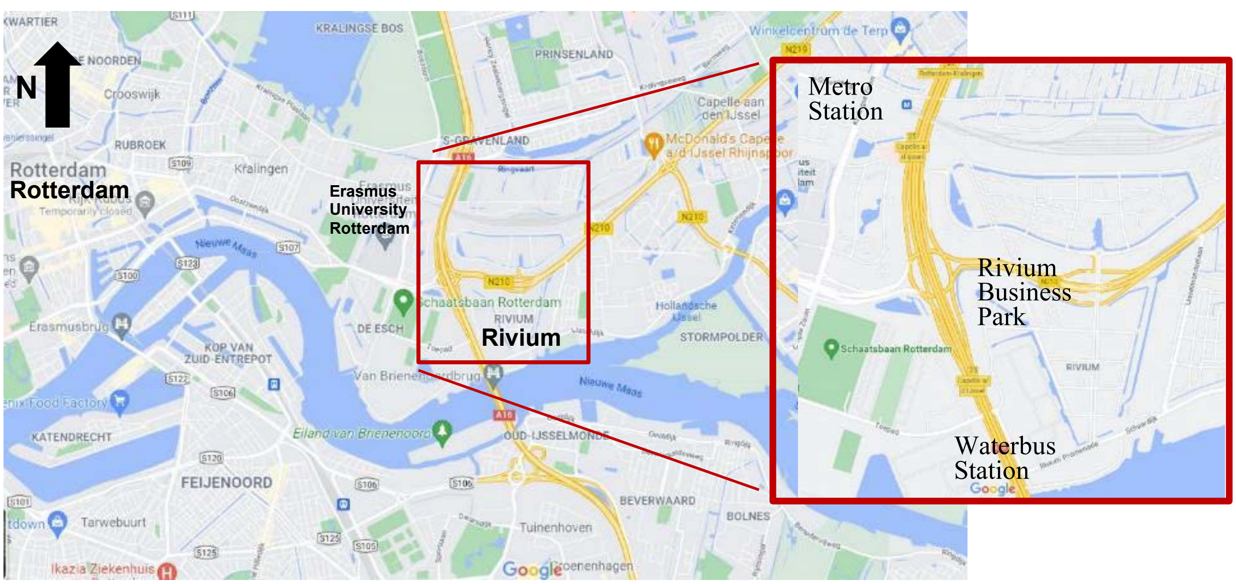


Figure 3-26. Proximity map of Rivium and ParkShuttle service area with central Rotterdam.

Source: Google Maps

Planning by the city of Capelle aan den Ijssel, the city in which the majority of the expanded system is located, envisioned that the line would be extended at some point beyond the

Rotterdam metro station to reach the nearby Erasmus University Rotterdam, located 0.5 miles from the station. The university's proximity to the metro station can be seen in Figure 3-26.

Technical Features of the New Vehicle – Progress toward deployment of the new third-generation vehicle design has been accomplished with the first certification under the draft AV research and development operations criteria prepared by the Netherlands, Experimenteerwet zelfrijdende auto. This new vehicle has a combination of old and new features that provide notable autonomous operational capabilities, including:

- Level 4 highly automated driving system with new sensing and artificial intelligence perception technologies, allowing the vehicle to operate without an onboard attendant.
- Larger passenger cabin with a total capacity of 22 passengers when configured with eight seats.
- A battery-electric-powered drive system that is capable of sustained speeds at capacity up to 38 mph (60 kph), although the operational design domain for the Phase 3 AV deployment will be limited to 25 mph (40 kph).
- Bidirectional operation with equal performance in either direction.
- Steerable drive axle that, when combined with the non-powered steerable axle, allows 25-foot-radius turn movements and a unique lateral "crabbing" maneuver upon approach to the station berth that enables high-precision docking.
- Vehicle doors on both sides of the passenger cabin, allowing "pinched-loop" route configurations with a reversable direction possible at any location without turning the vehicle.

Precision localization using onboard odometry, combined with sensors that track the vehicle's location with extremely high accuracy, are based on a grid of fixed magnetic markers in the pavement. Originally known as the "Free-Ranging on Grid" (FROG) system, this localization methodology has been the trademark 2getthere control system over the last 30 years, and it remains a valuable feature of the ParkShuttle vehicles. When combined with the lateral crabbing maneuver of four-wheel steering, each vehicle can accomplish precision docking at each station berth. This precision docking at the station platform provides sufficient accuracy such that wheelchair roll-on capability is possible without requiring any wheelchair ramps or bridge plates.

Figure 3-27 includes photographs of the station platforms with level boarding currently operating on the ParkShuttle transit system, exhibiting the vehicle's precision docking capability.

Figure 3-27. Precision docking allows wheelchair-level platform boarding at station berths.

Source: 2getthere, a company of ZF

Precision localization continues to be used where needed, but the vehicle's general localization is now utilizing more common technologies of conventional GPS/global navigation satellite system (GNSS) and sensor-based recognition of fixed landmarks, providing robust and resilient global and local navigation not dependent on any one system. The comprehensive sensor stack that allows all objects around the vehicle to be tracked also includes lidar, radar, cameras, and ultrasonic sensors—all of which are provided by the parent company ZF.

Opportunity charging in stations use in-road charging plates, with onboard battery equipment suitable for ultra-fast charging. This allows a fully discharged battery pack to be recharged in 11 minutes. To accomplish the fast charging in a station berth, the vehicle is precisely positioned over the charging pads when it docks at the station platform, after which it lowers onboard contacts to initiate the fast-charge cycle. By using the opportunity charging approach, the automated fleet management allows each vehicle's battery pack to be regularly recharged as it progresses through the station stops along its route. The battery charging process is managed in coordination with the passenger station stops, and it is fully automated. The principal advantage of designing the system to use automated opportunity charging in stations is that the operating fleet size can be significantly reduced compared to the conventional approach of having extra vehicles out of service for multiple hours per day as they recharge their batteries in offline storage facilities.

3.7.1 Challenges Faced and Lessons Learned

Throughout the second phase of operation of the AV shuttle service over the past 20 years, there have been provisions at several locations for roadway traffic to cross the shuttle's dedicated travel lane. These transitway/roadway junctions utilized crossing arms that operate under the control of the ParkShuttle's control system, similar in operation to railroad crossing arms as frequently experienced in the United States, but smaller in scale. Pedestrians are also allowed to cross at those locations when the crossing arms are raised. This simple means of using integrated roadway infrastructure to protect against conflicting movements between the AV shuttles, automobiles, and pedestrians was an evolutionary step toward the more sophisticated mixed-traffic operations that will be implemented in Rivium 3.0.

Introduction of the AV shuttle operating fleet into mixed traffic in the Rivium 3.0 expansion has been recognized as taking the Level 4 operation of the shuttles to a completely new level of complexity. In particular, design objectives were set to enable the vehicles to operate at speeds that complement existing traffic flow rather than impede it. This capability, in part, been addressed and enabled through the incorporation of "smart traffic signals" into the system design.

<u>**Smart Traffic Signals**</u> – As described in a 2020 article published in *Unmanned Systems Technology* magazine, the system specifications in the sidebar include "communications with smart traffic signals" as an integral element of the system design (refer to the link to that article in Section 3.7.2).

3.7.2 Reports and Reference Documents/Websites

Several technical publications have carried articles about the ParkShuttle technology over the last 2 years, with some discussion included about the Rivium 3.0 project. Links to these publications are provided below, as well as a link to the recent press conference video recording shown at the 2022 Consumer Electronics Shows by the parent company, ZF.

- Donaldson, Peter. 2020. "Autonomy to the four." *Unmanned Systems Technology* Oct./Nov. 2020: 24–35. https://www.ust-media.com/ust-magazine/UST034/24/#zoom=z.
- Galea-Pace, Sean. 2021. "The Future of Mobility." *EME Outlook* 40: 116–119. https://www.emeoutlookmag.com/magazine/issues/39-europe-middle-east-outlook-issue-40-march-21/116.
- Autonomous Transport Systems by ZF image video presented at ITS 2021: https://youtu.be/f743XusOqp8
- ZF Group. "Autonomous Transport Systems by ZF." YouTube video, uploaded Oct. 7, 2021. https://www.youtube.com/watch?v=wAgva8V_fgg.
  The discussion of ZF's autonomous shuttle technology begins at 7:45.

3.8 Site #8: Denver – Colorado Smart Cities AV Deployment Partnership

The Regional Transportation District's (RTD's) initial AV shuttle demonstration pilot project was called the 61 AV. It connected RTD's Peña Station on the LRT system A Line with offices located nearby within the Peña Station commercial complex. As reported in the first edition, the demonstration pilot concluded in August 2019. Since that time, Denver RTD has not undertaken any further AV deployments, in part due to lack of funding and the operational constraints imposed on RTD during the 2020/2021 pandemic.

However, RTD has taken an approach to leverage partnerships with other groups that assist with AV deployment in the region. RTD has worked with Colorado Smart Cities Alliance in their current planning initiatives for AV deployment projects and is open to working with other groups as well. RTD's involvement with the Colorado Smart Cities Alliance deployments is limited to projects providing connections to their transit service and will primarily focus on future marketing and integration of the AV services into the existing transit services and the RTD trip planner.

One current initiative that relates to RTD operations is focused on the Southeast Corridor. The work is identifying specific RTD stations for development through a focused station-area plan referred to as a Mobility Evolution Initiative. A StoryMap has been developed that introduces the seven stations being studied for advanced technology applications, each of which is envisioned to include AV technology deployments providing first-mile/last-mile access to the RTD stations. This planning will evolve and develop as AV technology advances and as project funding permits.

AV Shuttle Fleet Deployment in Golden, Colorado – Another major new AV shuttle project was accomplished within the Denver metropolitan area under the auspices of Colorado Smart Cities Alliance's cooperative program during 2021. This project was located on the university campus of the Colorado School of Mines ("Mines") in Golden, Colorado, on the far west side of the Denver region. This public research university is focused on science and engineering, particularly related to Earth, energy, and the environment. The city of Golden was also engaged as an active partner with Colorado Smart Cities Alliance and EasyMile in the project's deployment.

EasyMile, which has its U.S. headquarters in the Denver region, was a full partner in this initiative by providing a full fleet of nine EZ10 shuttle vehicles. The operating plan was for seven AV shuttle vehicles to be operated during peak periods on and around the Mines campus to provide essential transportation services to the student body.

Known as the "Mines Rover," this AV shuttle fleet was deployed with the original intent to operate on three different routes through Golden between August 2021 and July 2022. The routes shown in Figure 3-28 connected the Mines campus with downtown Golden. Operating primarily in mixed traffic, the AV shuttles traveled on campus roads and city streets at a maximum speed of 12 mph.

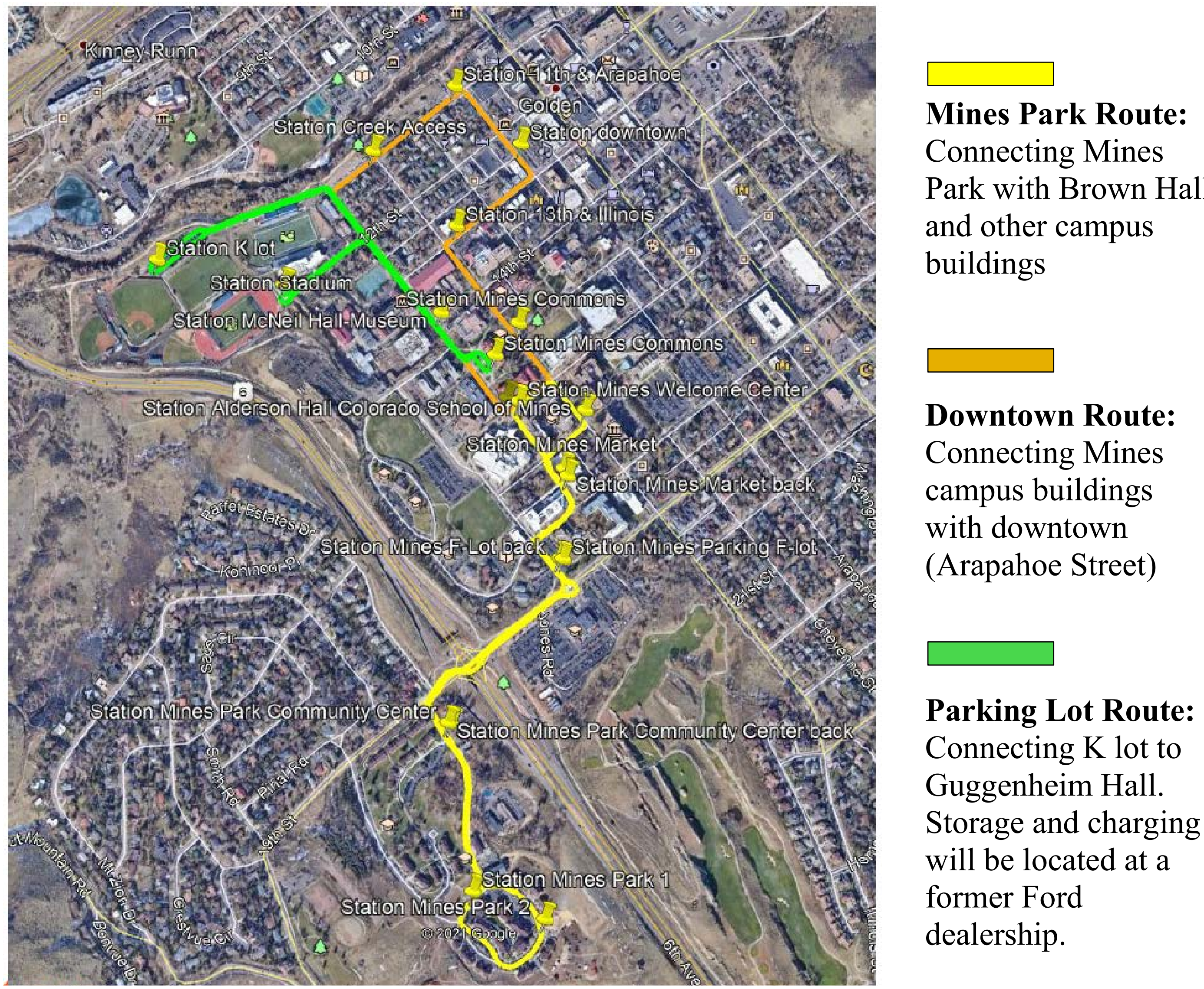


Figure 3-28. Golden, Colorado, AV shuttle routes for the Mines EZ Street pilot project.

Source: Colorado Smart Cities Alliance

Figure 3-29 shows one of the EZ10 shuttle vehicles deployed in the operating fleet. The operating environment of the AV fleet deployment was generally well suited for this low-speed shuttle operation, with some operational complexity—such as a roundabout at one location. Mines students on board each shuttle served as customer service ambassadors after being trained to monitor the vehicle's operations, and to take control when necessary to resolve situations in which the vehicle disengages from its ADS operation.

The city of Golden also invested in the project by ensuring that roadway physical infrastructure in the city street right of way was conducive to the proper operation of the EasyMile shuttles, including the transit stop signage, pavement markings, and, where required, concrete pads for passenger boarding locations.

Figure 3-29. EasyMile EZ10 shuttles operated in passenger service along the Golden city streets.

Source: Colorado School of Mines website

3.8.1 Challenges Faced and Lessons Learned

Funding of additional AV demonstration projects has been the primary challenge limiting RTD's further deployment of the technology over the past couple of years, even though there is a continuing interest in pursuing federal funding for other similar projects like 61 AV. To that end, the development of partnerships with other entities in the Denver area in pursuit of this funding has been an important approach for new projects in the near term.

Several significant challenges were faced on the Mines Rover demonstration pilot project. Their significance as insight for future deployments of all types of AVs also has implications for implementation of AMDs in general.

The net result of the challenges discussed below was that only three to four vehicles were able to be kept in service for the majority of the time, as compared to the planned seven-vehicle operating fleet.

1. **Impacts of Terrain** – The hills that the AV shuttles were required to traverse along the routes induced mechanical problems that were unexpected for EasyMile. Since the deployment was a partnership in which EasyMile was financially responsible for the maintenance and operations of the fleet, the resulting cost of repairs and the challenge of keeping sufficient vehicles in service were detrimental to sustaining the planned level of service.
2. **Vehicle Control System Sensitivity to the Physical Environment** – Driverless technology relies on sensors to map the vehicle's surroundings and scan for obstacles, and changes in those surroundings can influence operations. During the fall 2021 change of seasons, leaves blowing along the roadways would occasionally trigger emergency braking of the shuttles as the sensors identified them as obstacles.
3. **Asserted Compliance With FTA's ADA Regulations** – Even though the project was not funded by federal grants, the fact that the shuttles had the RTD logo on the side as one of the partnering agencies drew FTA's attention to the project. FTA asserted that the vehicle should comply with their full ADA regulations, including the installation of side rails on the wheelchair ramp and the installation of wheelchair tie-downs. This added further unexpected expense to the project.
4. **AV Shuttle Speed Differential With Other Conventional Vehicles** – With the vehicles operating at 12 mph in mixed traffic, operational conflicts of the AV shuttles with conventional human-operated vehicles occasionally occurred. Human drivers can get impatient and begin following too closely behind the shuttle. This can decrease the human driver's response time should an emergency stop happen in front of them. Also, human drivers would cut off the shuttles and unknowingly trigger emergency stops.

As a result of the major expenses being incurred by EasyMile and the associated reduction in operating fleet and passenger service levels, the parties involved mutually agreed to terminate the Mines Rover demonstration pilot at the end of the fall semester rather than continuing to operate the AV routes until July 2022.

3.8.2 Reports and Reference Documents/Websites

The following summary report on the 61 AV demonstration project was prepared by RTD staff and presented to the RTD Board in August 2019:

- RTD. 2019. *61 AV: An Autonomous Shuttle Demonstration Project, Final Report*. Denver, CO: RTD. https://www.rtd-denver.com/sites/default/files/files/2019-09/61AV-project-recap-aug2019.pdf.

The Autonomous Vehicle Colorado (AvCo) project at Mines is described on the city of Golden's website, with the article intended to brief the public on the significance of the pilot project and to advise them of the project's early conclusion at the end of 2021:

- City of Golden. 2022. "Autonomous Electric Transit Vehicles Pilot: Update on Mines Rover Service in 2022." Accessed April 3, 2022. https://www.guidinggolden.com/autonomous-electric-transit-vehicles-pilot.

Information on the Colorado Smart Cities Alliance 2021 initiative to execute the largest U.S. deployment of AV shuttles in one location at the Colorado School of Mines is accessible on the AvCo website. The associated video on the webpage can be viewed through the link below. It provides an overview of the significance to the industry of the Mines Rover deployment:

- AvCo. 2022. "AvCo – Autonomous Vehicles Colorado." Accessed April 3, 2022. https://www.avco.city/.

Lessons learned from the AvCo project are also available through a complete guide to autonomous transit deployment called the CityForward Playbook. The Playbook also includes pitfalls to avoid and key accomplishments broadly applicable to the global connected and autonomous vehicles industry:

- Stantec GenerationAV. 2022. "CityForward." Accessed April 28, 2022. https://stantecgenerationav.com/CityForward.

Finally, an interactive StoryMap has been prepared by the Colorado Smart Cities Alliance. Accessible through a link on their website, the StoryMap has been developed to describe the rich diversity of business and community interests through the Denver South Region service area, and the prospects of targeted first-mile/last-mile connections that include AV deployments as one of the possible options. Identified as the Mobility Evolution Initiative, the StoryMap describes seven targeted stations along the Southeast Corridor LRT line that are being studied for advanced technology applications for first-mile/last-mile connections as time progresses:

- Denver South, Colorado Smart Cities Alliance, and AECOM. 2020. *Mobility Evolution Initiative*. Denver, CO. https://storymaps.arcgis.com/stories/b4c894bb4f5146eb9973e5b2a64567f1.

3.9 Site #9: Gainesville – Autonomous Vehicle Pilot Project

The city of Gainesville received a grant from the Florida Department of Transportation in 2018 for the deployment of a low-speed AV shuttle that connects the downtown Gainesville area with the edge of the University of Florida campus. As reported in the first edition, as of the end of 2019, the deployment was still pending the initiation of passenger service utilizing the EasyMile EZ10 Gen 2 vehicles.

The two vehicles deployed in Gainesville are being provided and operated through a contract between the city of Gainesville and TransDev. The operation of these vehicles is contingent on the approval by NHTSA for "importation for testing and demonstration" under the provisions of what is called the NHTSA "Box 7" application submittal category. This application process is used to request special permission to import and operate vehicles that are not in compliance with FMVSS.

Testing, training of personnel, and mapping of the 1.4-mile Phase 1 route was authorized by NHTSA to begin at the end of July 2019 (a reinstatement of a prior authorization) and specifically permitted 2 months of these test operations. Then, in December 2019, NHTSA authorized the "research and demonstration" service allowing public passengers to ride the service along the Phase 1 route in mixed traffic.

Service during Phase 1 was initiated in February 2020, but operations were suspended only weeks later when NHTSA directed all EZ10 vehicle operations across the United States to cease after the passenger injury incident in Columbus (refer to the article on Site #1 in Section 3.1). In accord with NHTSA directives, the EasyMile vehicles were modified to provide seat belts and other audio and printed labeling safety advisements—a process that was completed several months later.

In August 2020, NHTSA reinstated its permission to begin the research and demonstration operations in passenger service along the Phase 1 route, connecting the SW Downtown Garage to the College Manor Apartments. The Phase 1 route operations continued throughout the early part of 2021, with appropriate social distancing protocols in effect due to the COVID-19 pandemic.

NHTSA gave permission for the initiation of Phase 2 operations along the route shown in Figure 3-30, utilizing a fleet of four EZ10 vehicles that had originally been imported by TransDev in 2018. The March 2021 NHTSA response to a December 2020 request from TransDev, the importer of the vehicles and the responsible party with respect to NHTSA approvals, gave specific permission to operate the vehicle in passenger service, but limited the authorized operations to the following very specific conditions:

> " … research and demonstration will be conducted along a 1.7-mile route connecting Gainesville Apartments (1) to the SW Downtown Garage (2). …The Vehicles will be operated at a maximum speed of 12.5 miles per hour and will service the general public. A trained safety operator, employed by Transdev, will be on board during the operation of the Vehicles to ensure passenger and vehicle safety. The Vehicles have emergency stop capabilities that allow for the safety operator to stop the vehicle immediately if there is an emergency. The safety operator can then re-engage the vehicle to continue its route in autonomous mode when the safety operator deems it safe to do so. The safety operator can also drive the vehicle in manual mode, using a hand control to move the vehicle forward, backward, left, and right."

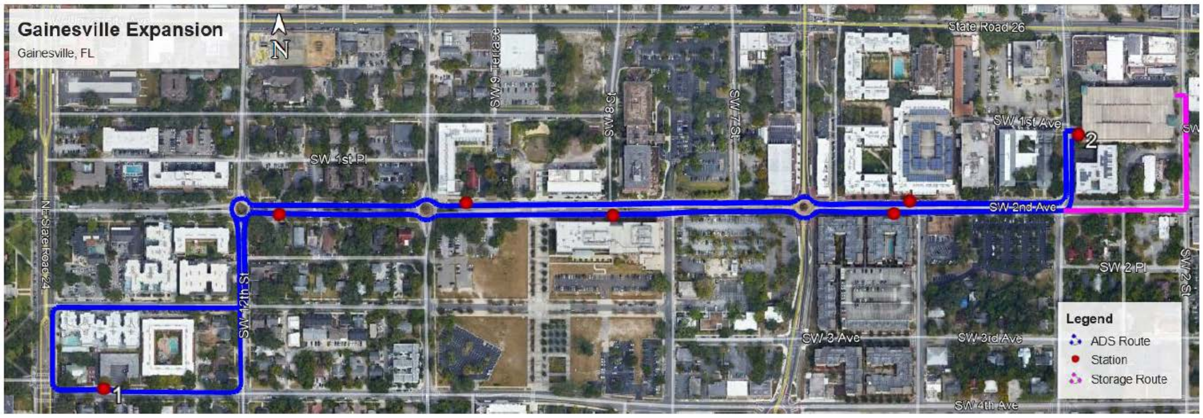


Figure 3-30. Phase 2 operating route for the Gainesville driverless shuttle demonstration pilot.

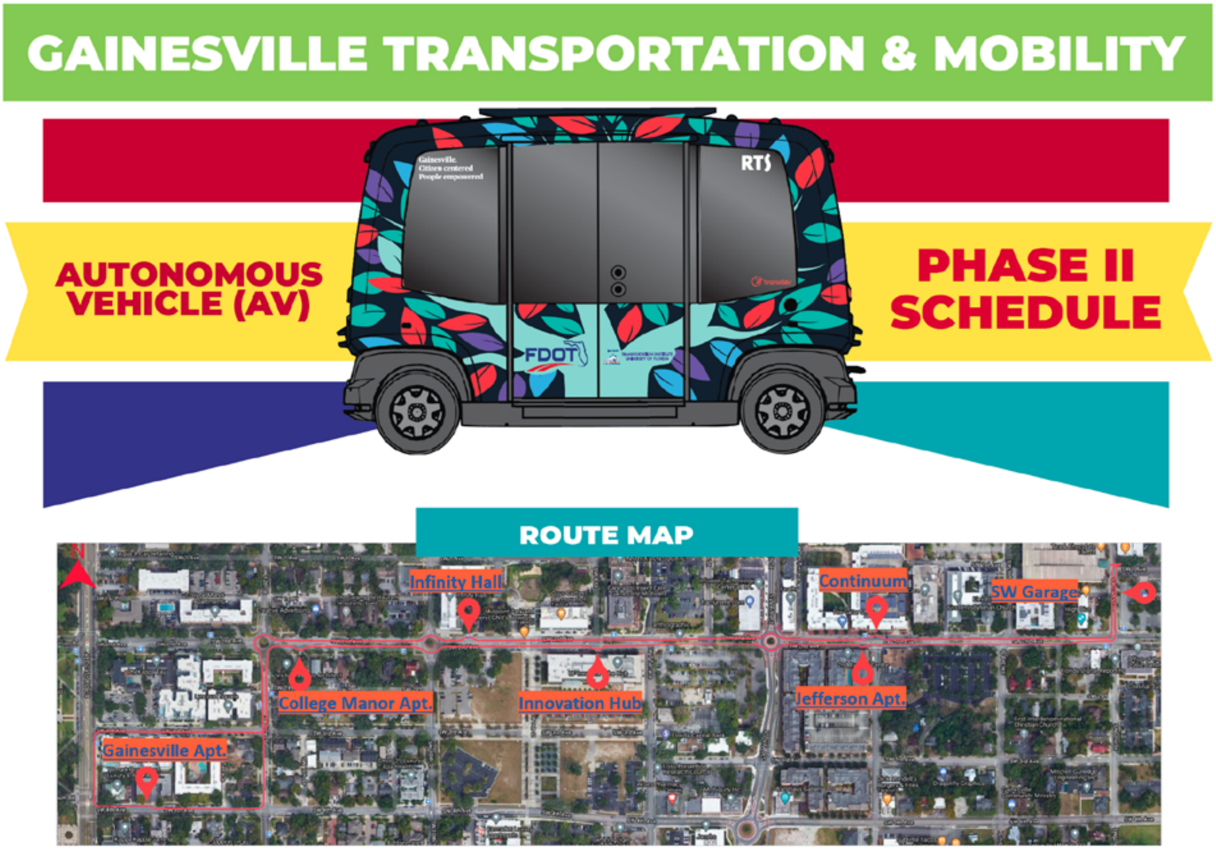
Source: City of Gainesville

Refer also to other typical NHTSA Box 7 stipulations in Appendix A, which are usually part of an NHTSA letter of authorization to import and operate low-speed AV shuttles manufactured outside the United States.

Phase 2 service began in June 2021, with the associated route schedule shown in Figure 3-31. The route is integrated into the operations of the Regional Transit System, providing public transit service under the auspices of the city's Department of Transportation and Mobility. The round-trip time for each vehicle, as shown on the schedule including station dwells, was 35–40 minutes depending on the time of day. Based on the NHTSA approval of a maximum of two vehicles in operation at any time throughout the day, the respective passenger level of service is a 20-minute headway and up to 15-minute travel time on board a vehicle.

The operating route encompasses roadway intersections that include one signalized intersection, three roundabouts, and several additional four-way-stop intersections. The complexity of safely operating through the signalized intersections is a key aspect of the research endeavor for the project, with the University of Florida and Florida Department of Transportation involved in the assessment of these connected vehicle aspects. The intersection at SR24 (SW 13th Street) and SW 4th Avenue is equipped with dedicated short-range communications as part of the university's "I Street Project," by which signal phase and timing data are provided to the AV shuttles, as well as vehicle communications alerting the traffic signal controllers of the AV shuttle's approach.

The EasyMile shuttles, shown in Figure 3-32, are being operated with a maximum speed of 12.5 mph, in accord with the NHTSA approval to operate the Phase 2 route. One of the important aspects of the RTS project's demonstration will be the assessment of the AV operations at this low speed in mixed-traffic conditions for all other vehicles operating along streets with a 25-mph speed limit. However, one of the considerations of the Phase 2 route selection was the relatively short city block spacing and other perturbations to traffic flow that typically limit average vehicle speeds to less than 35 mph.



AV Route

Outbound			Inbound	
SW Garage	College Manor Apt.	AV	College Manor Apt.	SW Garage
9:00	9:15	1	9:20	9:35
9:40	9:55	1	10:00	10:15
10:00	10:15	2	10:20	10:35
10:20	10:35	1	10:40	10:55
10:40	10:55	2	11:00	11:15
11:00	11:15	1	11:20	11:35
11:20	11:35	2	11:40	11:55
11:40	11:55	1	12:00	12:15
12:00	12:15	2	12:20	12:35
12:20	12:35	1	12:40	12:55
12:40	12:55	2	13:00	13:15
13:00	13:15	1	13:20	13:35
13:20	13:35	2	13:40	13:55
13:40	13:55	1	14:00	14:15
14:00	14:15	2	14:20	14:35
14:20	14:35	1	14:40	14:55
14:40	14:55	2	15:00	15:15
15:00	15:15	1	15:20	15:35
15:20	15:35	2	15:40	15:55
15:40	15:55	1	16:00	16:15
16:00	16:15	2	16:20	16:35
16:40	16:55	2	17:00	17:15

Figure 3-31. Phase 2 route schedule as it appeared on the RTS website.

Source: http://go-rts.com/

Figure 3-32. EZ10 Gen 2 vehicles operating on the Phase 2 driverless shuttle route.

Source: City of Gainesville

The transition between the completion of Phase 1 operations and the official startup of Phase 2 operations on June 2, 2021, was approximately 2 months. Activities during this time were focused on the testing of the onboard units (OBUs) providing the vehicle-to-infrastructure (V2I) communications links with the dedicated short-range communications-enabled roadside units (RSUs) and the associated signal phase and timing equipment at the signalized intersection. This approximate 2-month duration also provided sufficient time for review and approval of NHTSA's authorization to proceed with operations.

Funding for the AV driverless shuttle demonstration project supports operations through August 2022.

3.9.1 Challenges Faced and Lessons Learned

The following challenges and lessons learned have been identified by RTS based on the initial operations of the demonstration pilot project:

- **Vehicle Operating Speed** – The EasyMile current design parameters and the associated Box 7 application to NHTSA identified a vehicle operating speed between 10 and 15 mph, which was the basis for the NHTSA approval stipulating 12.5-mph maximum speed. This was a significant reduction from the performance that has been expected by RTS in their planning for a 20–25-mph maximum operating speed in mixed traffic.
- **Service Schedule** – The planning by RTS developed an operating schedule with level of service based on the criteria used for other RTS public transit routes. However, the final service schedule was constrained by the charging schedule of the battery-electric vehicle propulsion. The four-vehicle fleet is scheduled with only two vehicles in operation at any time, in light of the vehicle's maximum duration of service between recharging periods.
- **Vehicle Safety Attendant** – The original expectation of RTS was that the vehicle would be able to operate on the Phase 2 route without onboard attendants. However, EasyMile does not recommend operating without an attendant in mixed-traffic conditions, and the associated NHTSA approval to operate the imported, FMVSS-noncompliant vehicles is also based on the requirement that the attendant is continuously ready to assume manual control of the vehicle.
- **Operations During the COVID-19 Pandemic** – Social distancing protocols limited the capacity to only four passengers (including the safety attendant) throughout spring 2020

to fall 2021. Public health directives also required that masks be worn inside the vehicle, and the transit agency's safety procedures added extra cleaning activities to the vehicle interiors throughout the day.

- **ADA Requirements** – The EasyMile EZ10 vehicles are reported to be complaint with disabled passenger requirements for European applications, but the vehicle provisions were not compliant with the FTA regulations for ADA criteria in the United States. Specifically, the EZ10 vehicles have no wheelchair securement restraints, no ADA-oriented announcements on board the vehicle, and, in some circumstances of relative curb/boarding platform levels, the vehicle are noncompliant with FTA ramp angles for wheelchair loading.
- **Manual Operations** – The requirement for vehicles to be manually operated when navigating through the three roundabouts along the route was not expected by RTS.
- **Vehicle Sensors** – The expectations of RTS were that the vehicles could provide sustained operations in a driverless mode along the entire route in the Gainesville environment. However, there were a surprising number of circumstances and situations in which the vehicles were required to be taken out of service or encountered circumstances that caused a disengagement from automated driving functions, after which the vehicle was decelerated to a stop. The sensitivity of the sensor stack on the vehicles caused disruptions to operations in conditions like heavy rainfall, general proximity to tree branches moving in the wind, false object detection from reflective materials, and vehicle braking due to the speed and conflicting movements of bicyclists. Another design factor that was a surprise to RTS was that the Gen 2 vehicles do not detect and brake for any objects under a level of 18 inches above the running surface.
- **Significant Downtime** – The extent of service interruptions resulting from things like debris along the route, weather conditions of rain and wind, unavailability of operators, vehicle software upgrades, and other such factors has been higher than expected.
- **Data Sharing** – Sharing of data between the vehicle manufacturer and RTS has been more complicated and constrained than anticipated. The issues of sharing data about the AV shuttle operation need to be fully vetted during the contracting process to ensure the authority has full access to information and data it wants and needs.

Research studies of the public perception of the AV shuttle operations are currently underway through public opinion surveys and forums conducted by the University of Florida Transportation Institute. The research project is known as the I Street Living Lab, and the methodology used assesses the respondents' opinions before their exposure to the shuttle and after their actual experience riding and/or interacting with the AV shuttle operations. Findings of these before and after opinions to date have been summarized as follows:

- The comfort levels of shuttle riders went up after exposure to the shuttle.
- Pedestrian and bicyclists' attitudes toward the shuttle also shifted positively.
- Drivers, however, were frustrated with shuttle's slow speed, and their attitude shift was negative.

In addition, studies are underway to assess the effectiveness of the vehicle-to-infrastructure (V2I) communications at one traffic signal, which is equipped to transmit the signal phase and timing data to the vehicle. At this V2I-enabled intersection, connected vehicles can safely navigate the intersection using the left-turn signal for a protected turn, as well as initiate appropriate response to the signal phases such as braking to a stop on a red signal.

This research is ongoing during the continued operation of the Gainesville AV shuttle, and the University of Florida Transportation Institute is expanding their research endeavors to also study AV shuttle operations in other cities within Florida.

3.9.2 Reports and Reference Documents/Websites

Reports by the University of Florida Transportation Institute concerning the public perception of the AV shuttle operations and the vehicle-to-infrastructure (V2I) deployment at the signalized intersection will be produced after the conclusion of the AV deployment later in 2022.

Information on the autonomous shuttle operating route as it appears on the RTS website is accessible through the following links:

- RTS. 2022. “Route AV.” Accessed April 4, 2022. http://go-rts.com/route-av-autonomous-shuttle-sw-2nd-ave-12th-st-to-2nd-st/.
- RTS. 2021. “Autonomous Vehicle (AV) Phase II Schedule.” http://go-rts.com/wp-content/uploads/2021/06/AV-Phase-II-Schedule.pdf.

Articles from local Gainesville press and the University of Florida concerning the research initiatives can be accessed through the following links:

- Cunningham, Ron. 2022. “Lessons learned from Gainesville's experiment with driverless buses.” *The Gainesville Sun*, March 4, 2022. https://www.gainesville.com/story/opinion/2022/03/04/ron-cunningham-there-future-driverless-buses-gainesville/9322647002/.
- University of Florida Transportation Institute. 2022. “Gainesville’s Autonomous Shuttle Now Communicates with Traffic Lights.” Research Highlights, March 11, 2022. https://www.transportation.institute.ufl.edu/2022/03/gainesville-autonomous-shuttle-communicates-with-traffic-lights/.

3.10 Site #10: Babcock Ranch – Town Center and Neighborhood AV Transit Circulator

Following the shutdown of the EasyMile EZ10 AV shuttle vehicle operations during the pandemic, the Babcock Ranch district management decided not to restart operations. No further AV transport deployments are planned at this time.

However, the Babcock Ranch demonstration pilot did inspire another master planned residential development in Florida to deploy similar AV circulators. Lake Nona, Florida, is a well-known example of the ongoing inspiration of the early Babcock Ranch deployment. This master planned community near Orlando has deployed a Navya shuttle as a public transportation amenity for their resident population. The AV operations are managed by Beep, with further information found at their website: https://ridebeep.com/location/move-nona/.

Part 3: Five Cardinal Principles for AMD Implementation

- **First Cardinal Principle: A dense urban setting is important for an AMD.**
- **Second Cardinal Principle: Independent fleet operators and multiple AV technologies will be deployed in an AMD.**
- **Third Cardinal Principle: A management authority is a necessity for an AMD.**
- **Fourth Cardinal Principle: Intelligent roadway infrastructure is needed at multimodal junctions.**
- **Fifth Cardinal Principle: Intelligent roadway infrastructure must be integral to AV fleet operations and management.**

4 The Future of AV Operations in Complex, Multimodal Urban Settings

All the early AV deployment sites discussed in Section 3 faced common challenges when operating in multimodal mixed-traffic environments. The growing use of a geo-net approach to AV route planning is driven by this concern of mitigating the complexity of the operating environment. The intent of the geo-net approach is to select the specific roads and directions on which the AV will operate, thereby avoiding roads with high operational complexity.

An overarching purpose of NREL's research is to think beyond these types of limitations of AV deployment to understand what other elements of the urban setting must also change. In doing so, the research is focused on determining how to reach the goal of implementing AMDs sooner rather than later.

To further establish the foundation of this research endeavor in terms of the longer-term solutions necessary for AV operations in complex urban environments, the following questions should first be addressed:

- Why is it necessary to assert that AV transport will be important to deploy in the largest urban districts with the most complicated urban environments?
- Why not keep AV transport applications in simple, less complex operating environments until some future undetermined date?

The answers lie in the business case that justifies the investments necessary to deploy large fleets of AV technology. Fundamentally, the basic goal of completely removing the operator/safety attendant from the Level 4 automated vehicle must be realized before there will be any adequate return on investment for private enterprise. Equally important to the business case is to deploy the driverless vehicles in a setting in which there is a suitable demand for relatively short-distance trips, as any scenario where empty vehicles must be repositioned over longer distances (typically called "dead-heading") works against the business case criteria.

Dense urban districts that are large employment, residential, and retail centers or major activity centers like university campuses, medical complexes, and airports typically meet the basic criteria for the business case, since these districts have the greatest concentration of "trip-ends" in most American cities. Within such an urban district, which is defined by a geographic boundary, this concentration of trip-ends is quite suitable to support the necessary return on investment through fares paid by each passenger, ideally at a level at or below the price of current conventional transport services. This "business case" can be viewed as an attribute of the infrastructure in which the cost to operate can be recouped through investment revenue—such as with elevators, moving walkways, and escalators within large complexes.

This is the business case that will justify the large capital expenditures required for AV transport deployments over the coming decade. Safe and efficient AV operations must be able to occur in complex operating environments without any safety attendant on board while operating within a district with a high concentration of person-trips. Otherwise, AV deployments will continue to be limited to small-scale government- or private investor-funded research endeavors and pilot demonstrations in relatively simple operating environments.

However, the reality in such urban settings that provide a suitable concentration of trips is that the complexity of multimodal transportation operations sets a high bar for the AV technologies to clear for safe and efficient, driverless AV fleet operations. NREL studies have used the Houston Uptown district[18] as an example of the multimodal operational complexity of a dense urban environment in which an extensive application of AV technology is expected to occur over the next 5 to 10 years. Figure 4-1 shows the density of development in this large mixed-use district located within the urban core of Houston, Texas.

Figure 4-1. Houston's Uptown district is a case study of operational complexity.

Source: Houston Uptown Management District

The suitability of Houston Uptown as a reference point by which to evaluate the AMD concept is enhanced by the new bus rapid transit (BRT) line that runs within its spine arterial roadway. Known as the Silver Line, this BRT system alignment shown in Figure 4-2 provides an excellent semi-protected operating environment for automated transit, which makes it a candidate system for early deployment of automated buses in the near to medium term.

Integration of transit modes like the Silver Line BRT into the street system naturally increases pedestrian activity and internal district circulation, which in turn provides greater opportunity for AV applications that serve first-mile/last-mile connections to high-capacity transit. However, this induced pedestrian activity for transit access comes with the added impact of increased operational complexity due to the BRT line's location, with its passenger stations also located in the center of a major arterial roadway. As the BRT system ridership matures over time, the transit stations within the median of Post Oak Boulevard will draw large amounts of pedestrian

[18] Houston Uptown is one of the largest business districts in the country, with 38 hotels, 180,000 permanent residents, and 28 million square feet of office space. Uptown's 1,000 stores produced $4 billion in annual retail sales in 2019.

activity through the same intersections that experience high demand and heavily congested traffic operations.

Adding to this complexity of traffic operations is the presence of heavy pedestrian activity around the Galleria Mall, an extremely large retail center located adjacent to the intersection at Westheimer Road and Post Oak Boulevard, shown in Figure 4-2. The Uptown Galleria is the largest shopping mall in Texas and the seventh largest in the United States.

Traffic operations within the Houston Uptown district are also at times heavily impacted by freeway congestion that impedes access to this important district. As shown in Figure 4-3, this freeway traffic congestion often spills back onto the arterial roadway system. This peak-period traffic congestion on the arterial street system can then queue back into upstream intersections in the heart of Uptown. One such roadway intersection shown in Figure 4-3 is the same intersection shown in Figure 4-2 that has heavy pedestrian crossing activity.

Figure 4-2. Uptown district's new Silver Line BRT system.

Source: J. Sam Lott

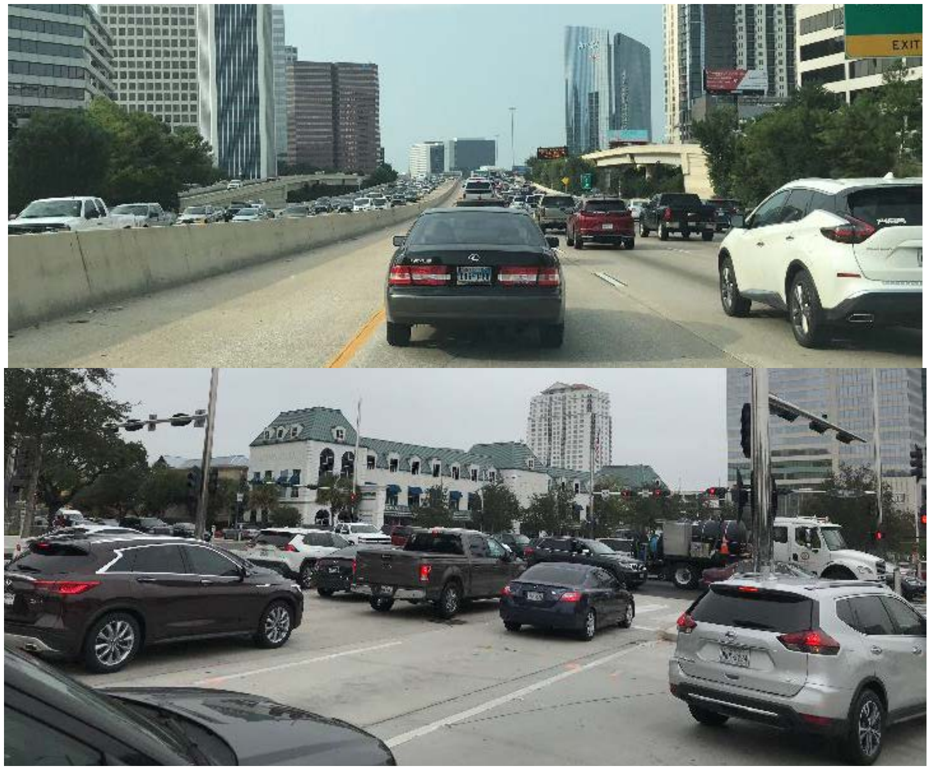


Figure 4-3. Traffic congestion on the capacity-limited freeway bisecting the urban district actually forces congestion back through the arterial streets that intersect the freeway.

Source: J. Sam Lott

However, the fact that this extensive traffic congestion impedes access to the district by automobiles actually creates the opportunity to provide valuable transit connections through the Silver Line BRT because it has direct access to the regional high-capacity transit system at both ends of its alignment. The connection between BRT and regional transit fosters the essential need for effective first-mile/last-mile connections within the Uptown district, which in turn induces the types of internal district person-trips that would be well served by AV fleet operations. A map of the Uptown area and its regional transit connections is included below in Figure 4.8.

4.1 Concept of an Automated Mobility District

The concept of an AMD was briefly described in Section 1, with an extract from the first edition of the *AMD Implementation Catalog*[19] repeated below:

> "An Automated Mobility District is a geographically confined district or campus-sized implementation of connected and automated vehicle technology for the purpose of publicly accessible mobility by which all the potential benefits of a fully automated mobility service can be realized."

NREL's Mobility Innovation & Equity Team further describes the characteristics of an urban district, which will typify the conceptual AMD as one having sufficient density to foster the level

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[19] Young and Lott. 2020. *The Automated Mobility District Implementation Catalog*. https://www.nrel.gov/docs/fy20osti/76551.pdf.

of internal circulation that is well suited for AV transport service. Figure 4-4 illustrates this concept as a district commonly found in a dense urban environment—places like a large urban district, a major activity center like an entertainment district or a large airport, or a sufficiently dense campus environment such as a major university or medical complex.

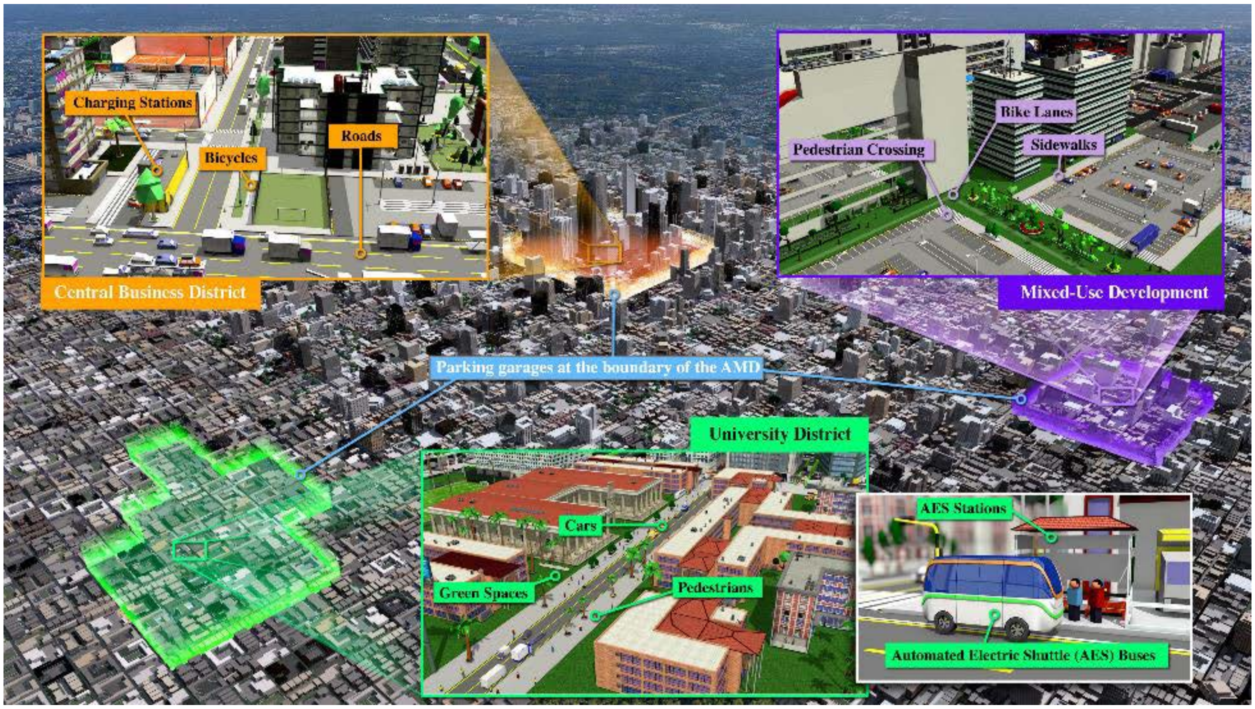


Figure 4-4. The AMD concept was developed at NREL to evaluate operational complexity.

NREL's studies of conceptual AMDs have assessed the implications for energy use when diverse mobility transport services are provided within these urban operating environments. NREL has now added to this study their findings of the 10 early AV deployment sites described in Section 3. From the findings, observations, and conclusions laid out in Sections 1 and 2, the research has led to the establishment of five cardinal principles for large-scale AV deployments within AMDs.

The first cardinal principle concerns the challenges AV developers are facing and the related aspects of the business case that drive AV deployments in dense urban districts and major activity centers—i.e., settings conducive to the creation of AMDs. The second cardinal principle establishes that AV technology will be primarily deployed in managed fleet operations over the coming few decades.

Based on the likelihood of multiple AV fleets being in service within an AMD, a third cardinal principle advises that each AMD will need the establishment of an authority having jurisdiction over multimodal operations within the district's roadway system. This is particularly important when the multiple fleets of automated vehicles are operating in mixed traffic, since this requires AV fleet vehicle interaction with human-operated vehicles and other vulnerable roadway users like pedestrians, bicycles, wheelchairs, and scooters. The applicability of such a jurisdictional authority can be understood by considering the types of districts and major activity centers that already have such a management authority in place by the nature of the activity center. Examples would be an airport authority or a university campus administration having jurisdiction over essentially every form of transportation within their property.

These first three cardinal principles are discussed below in more detail, and the fourth and fifth cardinal principles are addressed in Section 5.

4.2 First Cardinal Principle – Importance of the Dense Urban Setting for an AMD

The previous discussion concerning roadway operational complexity used the Houston Uptown district as an example. This district also exemplifies urban density and mixed-use development that creates the basic ingredients shaping the concept of an AMD.

Figure 4-5 shows in the top photograph the new Silver Line BRT operating through a segment of Post Oak Boulevard—the arterial backbone of the district. The photo also shows in the foreground office towers that were built in the 1970s, and in the background new residential towers that have been built in the last few decades. This constant growth and revitalization is indicative of the active trip-making development that feeds internal district circulation and connectivity.

Houston Uptown district reflects all the person-trip generation elements that would be well served by a fully automated AV transport system operating strictly within the district boundaries (often referred to as a “geofenced” area). Uptown also fits the essential elements that support the business case for private enterprise to deploy their AV fleet to serve that demand. Uptown further demonstrates the major operational difficulties that AV technology deployment must overcome if the goal of automated mobility is to be fully reached. Thus, Houston Uptown is a representative AMD location of the future, where operation of AVs providing public mobility alongside various other modes is critical to further health and growth of the district.

Figure 4-5. The Silver Line BRT alignment transitions from aerial on the north end to at-grade on the south end through the Uptown district. Top: At-grade segment of the BRT Sliver Line alignment passes through office and residential towers that span 50 years of development activity. Bottom: View looking south along the IH-610 West Loop freeway, where aerial BRT alignment transitions to the center of the freeway to descend to grade.

Source: J. Sam Lott

4.3 Second Cardinal Principle – Independent Fleet Operators and Multiple AV Technologies Will Be Deployed in an AMD

One clear trend within the AV development community is that to achieve a significant deployment of fully automated transportation within an AMD, the conditions will require dedicated vehicles[20] in managed fleet operations. This in turn will foster multiple AV fleets operating within a single urban district under the management of different fleet operators. This is already evident in various other non-automated modes such as transportation network companies, taxis, various micromobility providers, and limousine services, in which competition for consumer demand in the open market invites multiple fleets. For example, even Waymo and Cruise—both automated transportation network companies—are currently operating in San Francisco, California.

As such, a key characteristic assumed for the AMD concept is that multiple AV fleets will be in service within the district, each having its own unique automated driving system control technology by which SAE Level 4 vehicle operations are accomplished. Also, by the nature of fleet operations on a large scale within a single district (e.g., 50 to 500+ vehicles), each fleet will have its own supervisory system and corresponding support staff in place to manage each AV fleet's operations. This supervisory control and support will not only manage and oversee normal operations, but also the necessary response to failure conditions, including incidents involving a vehicle shutdown (disengagement) such that the vehicle is brought to a stop. Fast and efficient failure response and recovery of failed (stopped) vehicles from active travel lanes or street curbfronts is one of the principal responsibilities of the operations staff.

This assumption of future managed fleet operations in dense urban settings conducive to an AMD is consistent with not only what is being demonstrated in the present status of AV deployments and continued R&D, but also with the AV developer indications of how AV transit and AV ride-hailing services will be provided in the near to medium term. Thus, the proposed multi-fleet operating condition is meant to be applicable by the general target year of 2030, when it is anticipated the AMD concept will be mature and replicated in many places.

Examples of different types of AV fleets, as depicted in Figure 4-6, would be AV transit operating in on-demand dispatch service and transit operating on established schedules along fixed routes. Such services could be complemented by AV taxi and AV Uber/Lyft type of ride-hailing car services. These various types of transport services could all provide internal circulation within the district, as well as first-mile/last-mile connections to high-capacity regional transit stations within or nearby the AMD.

The multiple types of AV fleet vehicles are envisioned to include small "personal" vehicles designed to carry single travel parties directly between their origin and destination "stations." This small vehicle class would typically be classified as on-demand, ride-hail service mode using vehicles with capacities of four to six passengers. It is also possible that this class of vehicle could serve several small (one- or two-person) travel parties that have chosen to share their ride together.

Larger vehicles designed specifically for the ride-sharing operation would also fit in the on-demand service mode in which multiple travel parties commonly share the same vehicle between dominant origin and destination pairs, thus aggregating demand. These medium-size vehicles seating 8 to 15 passengers have been deployed as "low-speed AV shuttles" in the early development stages of the multiple sites described in the first edition of the *AMD Implementation Catalog*, with their status after further development in recent years addressed in Section 3.

[20] SAE J3216, Section 4.2 (July 2021), defines an automated driving system-dedicated vehicle as "a vehicle destined to be operated exclusively by a Level 4 or 5 ADS for all trips within its given ODD limitations (if any)."

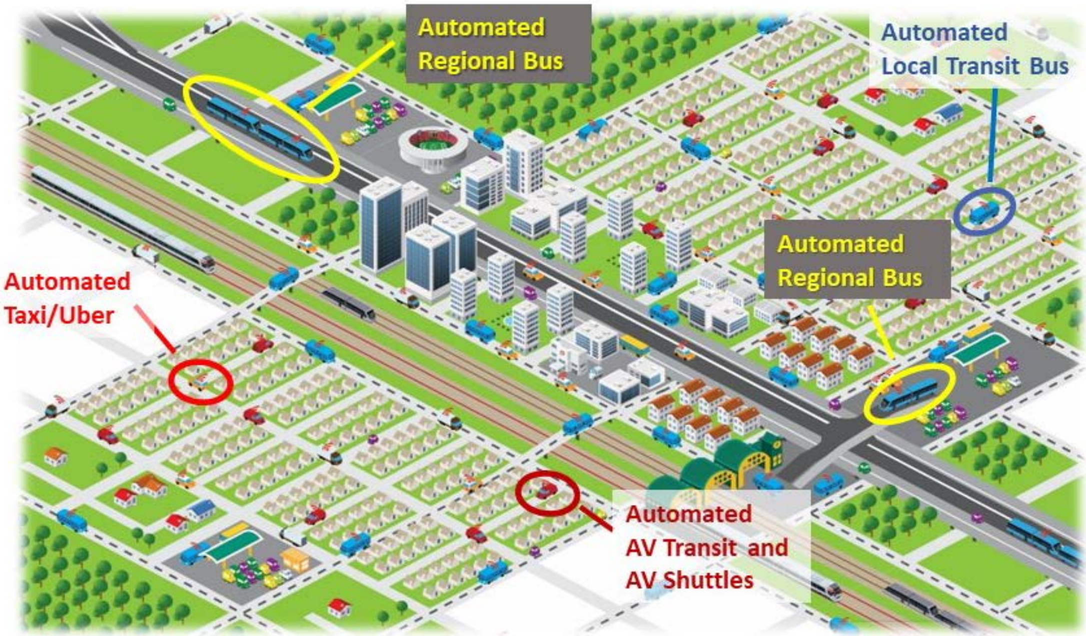


Figure 4-6. A conceptual urban district with multiple AV fleets in service.

Source: Houston-Galveston Area Council

To these smaller vehicle classifications will be added the conventional "transit" vehicles the size of the Silver Line BRT buses shown in previous figures, typically operating on fixed routes under fixed schedules. Several bus companies and their partnering AV technology developers are working to develop this full-size class of AV bus, and the initial deployments are expected within the next several years. This initiative to deploy full-size AV buses is described for Houston METRO's plan as part of the Automated Bus Consortium, addressed in Section 2.1 (see Figure 2-5).

In addition to the passenger transport vehicles, an AMD will have automated vehicles designed to carry packages and goods also operating along its roadways, like the Nuro vehicle shown in Figure 4-7.

The illustration in Figure 4-6, depicting a complex AMD, was taken from the Houston-Galveston Area Council's studies of future major urban districts with these types of automated mobility modes. In the case of the conceptual plans for Houston, the intra-district transport has been envisioned to connect public transit passengers to a regional automated bus system.

Figure 4-7. Package and cargo transport also represented among the AV fleet operations.

Source: Nuro website

With respect to the Uptown district, its configuration provides an example of how these various AV transport technologies could be integrated into an existing district to form an AMD. The graphic shown in Figure 4-8 illustrates how a multimodal transportation system could conceptually transform the Uptown district to operate as an AMD by 2030. The figure shows the new Silver Line BRT system that connects between one major transit center on the north to another new transit center on the south (both identified by circles). It is strategically important to note that the two transit centers on the north and south provide direct transfers from the Houston METRO Regional Busway system to/from the Silver Line BRT. This regional high-capacity transit system operates in dedicated high-occupancy vehicle lanes within the nearby east/west freeways that continue into the Houston CBD located 7 miles east of the Uptown district. The extensive 100-mile-long high-occupancy vehicle lane system that Houston METRO has built in cooperation with the Texas Department of Transportation is placed primarily within the medians of Houston’s radial interstate freeway system.

Figure 4-8 also shows how the north/south Interstate 610 West Loop freeway bisects the heart of Uptown that is served by the BRT line, separating the west side from a large component of high-rise office and residential towers on the east side of the freeway. This area is anticipated to greatly benefit from multiple AV fleets in operation on the district’s roadway network, providing first-mile/last-mile connections to the Uptown Silver Line BRT system on the other side of the freeway, while also providing internal circulation throughout Uptown.

One interesting aspect of using the Houston Uptown district as an example of a potential future AMD is that both the Silver Line BRT and the regional high-occupancy vehicle busway system are strong prospects for early conversion to AV operations in light of their semi-protected transitways. The Uptown Silver Line BRT system alignment runs north and south along a 4-mile length. The 2-mile-long at-grade transitway on the south end is placed in the median of Post Oak Boulevard, whereas the aerial transitway on the north end runs adjacent to and over the West Loop Freeway, as shown in Figure 4-5.

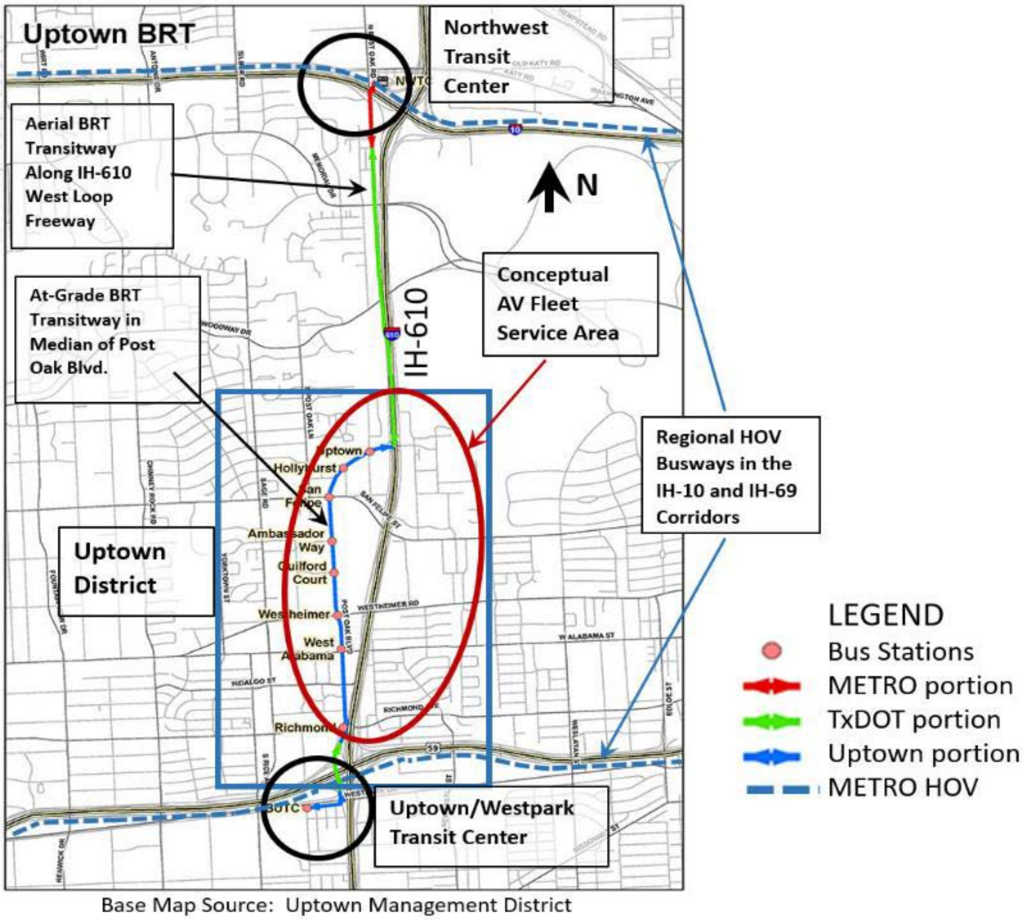


Figure 4-8. Houston's Uptown district provides an excellent example of a future AMD.

4.4 Third Cardinal Principle – Necessity of an AMD Management Authority

Creation of an AMD and the prospect for having multiple AV fleets operating within the district brings with it the need to manage the operating conditions. This operational management of the multimodal transportation system would include managing the design and deployment of the transportation infrastructure, and in particular the deployment of intelligent roadway infrastructure. See further discussion that follows in Section 5 concerning IRI. A legal management authority overseeing transportation operations and the associated infrastructure should be established/defined for each AMD.

Uptown is an urban center that already has an established management authority overseeing the general transportation system and its infrastructure. A legally defined Uptown Management District was established by the Texas State Legislature in 1987, which, as a quasi-governmental entity, provides an example of a prospective AMD management authority. The management district of this dense urban center has geographic boundaries defining the area of its jurisdiction.

Within this context, an AMD management authority would be created in the form of a quasi-governmental agency to monitor and manage the operating environment of the automated transport systems within the district.

This management authority would also have jurisdiction over key aspects of AV fleet operation, including the overall roadway operational management policies and the associated district-level management of the funding allocated for improvements to transportation infrastructure.

In addition, the AMD management authority would prescribe the operational rules for failure response with regard to AV fleet vehicles in the form of both individual vehicle fallback actions, as well as the failed vehicle recovery protocols to be followed by the respective fleet manager's operations staff. Typically, a vehicle's fallback condition, which is initiated when there is a vehicle failure or when the vehicle passes outside of its ODD, would cause the automated controls to bring the vehicle to a stop. It is proposed that the jurisdictional authority's rules and protocols would determine how and where the vehicle should come to an acceptable stop to minimize traffic flow disruptions, as well as guidelines of when and how, with respect to traffic management, to execute recovery.

With regard to safety when multiple AV fleets are operating within the district, it is proposed that the responsibility of the AMD management authority would be to take a "system-level" approach to safety assessment and risk mitigation. This top "system" level would encompass the multiple AV fleets, each with its own unique blend of AV technology applications.

The system safety assessments performed by the AMD management authority would be addressed through a safety case performed for each roadway junction to determine if intelligent roadway infrastructure is required for deployment to mitigate safety risks. In our current day with traffic signal systems and ITS technology applications, this development of a safety case could be equated to a traffic warrant study. And as with traffic warrant studies, some roadway intersections may be judged to not require IRI applications, with the AV's in-vehicle sensing and perception fully capable of protecting its travel through that location.

The AMD management authority would also be responsible for the operational management of the multimodal junctions that add complexity to the overall roadway operations environment. This would include those intermodal junctions where pedestrians transition from pedestrian mode to their selected transport mode. The most obvious intermodal junction would be a transit station for fixed-route operations, as shown in Figure 4-9. In the example case of the Uptown district, the Silver Line BRT stations are in the middle of Post Oak Boulevard. This placement of the intermodal junction adds complexity to the adjacent roadway intersections, where many pedestrians travel across the vehicular lanes to access the station boarding platforms. Such intermodal junctions would be individually addressed in the AMD management authority's safety case assessment, and from these assessments would come operational rules and cooperative protocols when such facilities are shared between different AV fleets.

The second most common intermodal junction would be the approved curbfront for use by ride-hailing services and on-demand transit services. This second type of junction may be as simple as a curb along the city street, or it could be a more complex configuration of curbs off the main street alignment exhibiting similar features to those of the transit station, perhaps as a major destination or attraction.

Figure 4-9. Example of an intermodal junction where pedestrians become passengers on board automated mobility transport vehicles.

Source: J. Sam Lott and Houston Uptown District

5 Large-Scale AV Transport Systems With Intelligent Roadway Infrastructure

The transportation system management challenge in dense urban settings involves focused attention to the safety of all roadway users, while also meeting operational efficiency goals. This requires operational traffic management in real time to achieve efficient traffic flow with increased capacity. With improved traffic operations, the goals of optimizing energy management across all vehicular modes and reducing vehicular emissions can also be accomplished.

The challenge that has been addressed by proactive traffic management over the last century has been primarily focused on maintaining safe roadway operations in complex urban settings, particularly at roadway junctions. Safety remains a major challenge with modern 21st century roadways, as evidenced by the fact that about half of automobile crashes occur at roadway intersections.

Thus, the objective of large-scale AV deployments must also be to move large quantities of vehicles through roadway intersections more safely than can be accomplished today when all vehicles are operated by human drivers. Accomplishing this objective of increased capacity and safety with AV fleet operations must also include the goal of protecting conventional human-operated vehicles, as well as the other roadway users like pedestrians and active transportation modes of bikes and scooters.

The challenge becomes more difficult when considering that some of the early AV deployments in mixed traffic have shown that the speed differential between the human-operated vehicles and the AV low-speed shuttles has created a higher risk for accidents due to human driver impatience. This is reported for both Denver/Golden (Section 3.8.1) and Gainesville (Section 3.9.1).

Complex operational environments such as that of the Houston Uptown district raise the critically important question, “How do you manage roadway operations in such a dense urban environment when a significant component of the traffic flow comprises AV fleet vehicles?”

The following discussion serves to provide the answer to the challenge posed by this question.

5.1 Transportation Management Challenge of Multiple AV Fleets Operating in Mixed Traffic

We learned 100 years ago that with the radical transformation of transportation from horse-drawn wagons and carriages to the automobile, the dynamics of roadway operations made the urban transportation operating environment much more complex, especially at street intersections. The technology transformation at the time from horse-drawn carriage to automobiles often required an “intelligent authority” to be placed in charge of the safe and efficient progress through each major roadway junction. Figure 5-1 shows a photo from 1910 of how this was addressed in London.

Figure 5-1. London's complexity of traffic operations 100 years ago brought the realization that an intelligent authority must be placed in charge of roadway intersections.

All of these multimodal aspects are the type of operational management concerns traditionally addressed by the "authority having jurisdiction" over the traffic control systems and roadway design features. The progression of roadway intersection management over decades has resulted in the digital signal control devices that are prevalent at nearly 300,000 intersections in the United States today. As we begin an equally radical transformation of our transportation system into one with automated vehicle operations, our challenge then comes in establishing an appropriate roadway intersection "traffic cop" authority that will be responsible for safe, efficient, and sustainable roadway operations, extending the functions and ability of today's traffic control to accommodate AVs, as well as various other modes.

5.2 New Sensing Technology for Managing Multimodal Environments

Whereas the solution for managing complexity of intense multimodal traffic operations 100 years ago involved placing a human in charge of individual roadway intersections, in the 21st century we must advance the capability of placing dedicated artificial intelligence as the "traffic cop" responsible for managing multimodal operations at each roadway intersection.

Current research is expanding the tools that can be applied to assist modern-day traffic signal systems. In addition to improving safety, advanced technology will help optimize and increase safety of traffic operations through major intersections.

This attention to roadway intersections has added importance when considering that the early years of AV development have illustrated how safety of pedestrians and other active modes like bicycles is particularly difficult to ensure for machine sensing and intelligence. When left to the ability of an individual vehicle (whether automated or manual) to detect and respond properly at complex roadway intersection environments, non-vehicular roadway users are more vulnerable than vehicular traffic. This concern for protecting vulnerable roadway users like pedestrians makes the new concept of "cooperative driving automation" equally important to deploy on both AV fleet vehicles and roadway infrastructure.

IRI research is exploring the use of sensing technologies like lidar, radar, and video cameras combined with traditional sensor and connected vehicle data to enhance the detection of vulnerable roadway users like pedestrians and people using various lightweight wheeled devices such as wheelchairs or electric scooters. When such new sensing technology is appropriately fused such that all objects in the field of view are confidently and accurately perceived at a major roadway intersection, a new term of "intelligent roadway infrastructure" is proposed.

As noted above, the combinations of modes and intensity of traffic operations create a situation that is beyond what an individual automated/autonomous vehicle is capable of navigating in a safe manner while maintaining a reasonably high operating speed that matches speeds within the flow of human-driven vehicles. The solution to these challenges over the coming decade will be found in the development of next generation traffic control systems with much greater spatial perception, referred to herein as IRI.

Figure 5-2 illustrates the sensing agents that will facilitate new traffic control tools that equip roadway infrastructure with the same type of sensing technology and artificial intelligence perception that is being applied within the AV itself. Such sensing technology applications to roadway infrastructure are conceptually the same as used in AV sensing functions, but with the sensing agents fixed in place at critical roadway intersections and distributed such that "blind spots" are eliminated. Whereas vehicle-based sensing is fundamentally limited by line of sight from the vehicle, infrastructure-based sensing can leverage optimal sensor placement through the intersection domain that avoids blind spots, developing a "digital twin" that tracks every roadway participant to a high degree of accuracy and confidence. This approach to roadway infrastructure sensing and perception is now being actively investigated for use in a new generation of traffic control and management systems.

Current research is studying the effectiveness of sensor detection for vulnerable roadway users, like the people crossing the street in wheelchairs shown in Figure 5-2. This photograph was taken at the same general location in the Houston Uptown district as that showing heavy traffic congestion in Figure 4-2 and Figure 4-3. This combination of heavily congested traffic and high activity levels of vulnerable roadway users is the type of intense, multimodal operating conditions that the next generation of roadway traffic control systems must be capable of managing to ensure large-scale AV fleet operations are safe and efficient for all modes.

Figure 5-2. Sensing and perception agents proposed for roadway infrastructure applications

5.3 Fourth Cardinal Principle – Intelligent Roadway Infrastructure Is Needed at Multimodal Junctions

The fourth cardinal principle comes from this essential requirement to manage the complexity of roadway traffic that includes AV fleet vehicles passing through major junctions such as arterial street intersections. This cardinal principle can be stated as follows:

> AMD management authorities will need to deploy what will be referred to as intelligent roadway infrastructure in order to adequately manage the complexity of multimodal traffic operations involving multiple AV fleets.

This cardinal principle is drawn in part from the precedent that has been set by the protection of automated guideway transit system junctions using communications-based train control technology over several decades. There have been 50 years of automated guideway transit deployments and associated standards development. One key element that is essential in communications-based automated train control systems is junction "interlocking," which highlights a missing functional element within current AV technology deployments.

This automated train control precedent involves fully automated transit vehicles safely operating through guideway junctions under the management of dedicated communications-based train control equipment that is placed at a specific junction location. This comparison between automated guideway transit and AV fleet operations has been described in an article published in the *SAE International Journal of Advances and Current Practices in Mobility*.[21] This paper was developed by NREL and its affiliated consultants and was originally presented and published in the proceedings of the June 2021 Business of Automated Mobility Forum. The paper references

[21] Lott, J. Sam, Stanley Young, and Lei Zhu. 2022. "Safe Operations at Roadway Junctions – Design Principles from Automated Guideway Transit." *SAE International Journal of Advances and Current Practices in Mobility* 4 (1): 260–269. https://doi.org/10.4271/2021-01-1004.

the subsystems of automated guideway transit systems described in the IEEE 1474 standard.[22] These automated guideway transit automated train control subsystems are correlated with what could be considered the functional control subsystems of an automated roadway vehicle (see Figure 5-3).

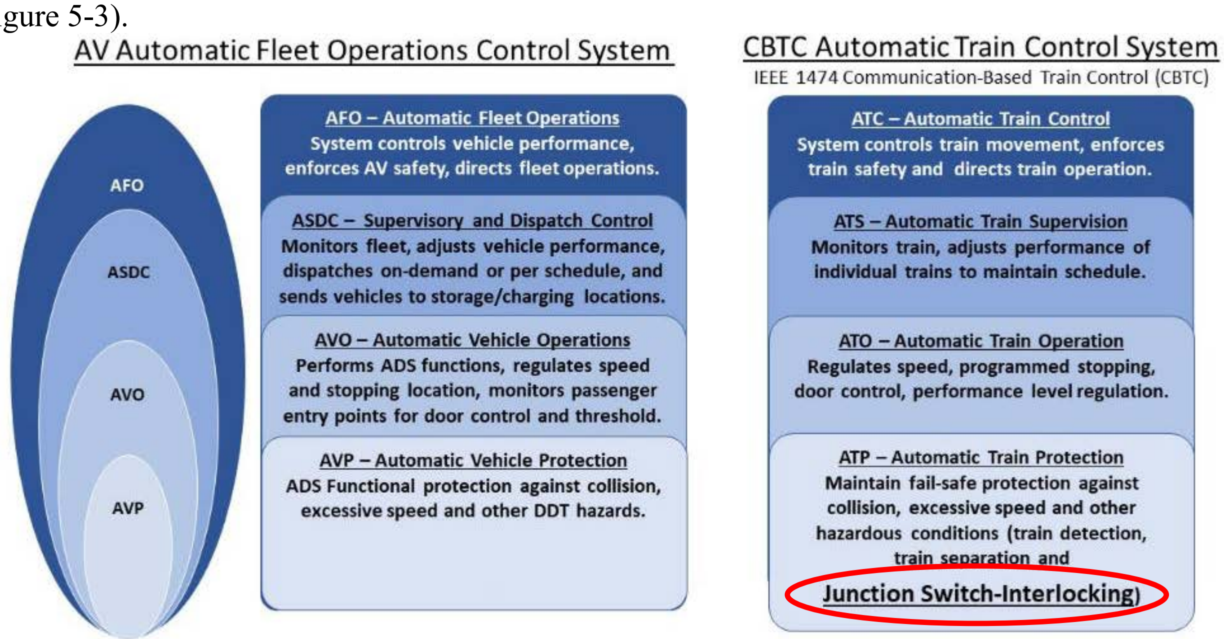


Figure 5-3. A systems view of AV transit and fleet operations drawn from automated guideway transit experience as defined in the IEEE 1474 standard

The equivalent subsystems for AV fleets are described in the figure as:

- **Automatic fleet operations** – The overall control system that encompasses both onboard and other equipment not located within the vehicles.
- **Automatic supervisory and dispatch control** – Comprising primarily the software-based systems that reside in an operations control center manned by operations staff.
- **Automatic vehicle operations** – The onboard software, sensors, and control elements performing the vehicle's self-driving functions.
- **Automatic vehicle protection** – Functional sensor, artificial intelligence, and onboard equipment that continuously act to protect the vehicle from crashing into other objects as part of the dynamic driving task.

From the illustration in Figure 5-3, the functional equivalent of what is called "junction switch interlocking" in the communications-based train control automated system controls is missing from the equivalent functions for AV fleet vehicle operations.

For comparison and illustration, Figure 5-4 illustrates a fleet of automated vehicles being dispatched to provide "ride-hailing" services (or on-demand car services, fixed-route transit, etc.), identified in the graphic as "Vehicle Technology #1." Consistent with the nomenclature of its automated control subsystems described in Figure 5-3, the graphic for Vehicle Technology #1 has its own unique supervisory and dispatching system, and a unique combination of

[22] IEEE. 2004. "IEEE Standard for Communications-Based Train Control (CBTC) Performance and Functional Requirements." IEEE 1474.1-2004. https://doi.org/10.1109/IEEESTD.2004.95746.

technologies to perform the automatic vehicle operations and automatic vehicle protection functions as it maneuvers through mixed traffic within the urban center. This fleet technology could be any one of multiple companies currently developing this model of automated mobility for their planned deployment in Level 4 operations over the next 5 to 10 years.

Also shown in Figure 5-3 is the automated functional control subsystem of IRI located at a roadway intersection where two major arterial streets cross, and where heavy pedestrian and other active transportation modes converge. This IRI is the functional equivalent of junction switch interlocking in Figure 5.3 for communications-based train control. The AV Fleet #1 vehicles are safely guided through the intersection by intelligent roadway infrastructure deployed at that location, depicted in the figure graphic as an IRI intersection.

Figure 5-4. Next-generation traffic control technology will apply IRI to protect multimodal junctions.

Note that the role of the IRI intersection is to provide safe passage protection at the junction to all vehicles in the Vehicle Technology #1 fleet, as well as to other AV fleets. The referenced paper published by SAE provides a detailed discussion of this essential safety role of intelligent roadway infrastructure.

SAE's definition of cooperative driving automation has been discussed throughout this document. The application of infrastructure-based sensing and control functions inherently assumes CDA functionality, but at a level that goes well beyond vehicle-to-vehicle communications with simply status sharing, intent sharing, and agreement seeking between multiple AV fleet vehicles. This CDA functionality must also occur between the dedicated, locally configured IRI and the AV fleet vehicles operating through a specific intelligent intersection's safety zone.

In the conceptual 2030 scenario of an AMD with multiple AV transport fleets in service, all AV Fleet Technology #1 vehicles would be designed, tested, and deployed to respond to the safety protocols for the IRI intersection in accord with what has been defined by the AMD management authority.

In the same way, Figure 5-5 illustrates how AV Fleets #2, #3, and #4 have been coordinated in their designs to respond in the same way to the IRI directives that are transmitted in real time within each IRI intersection's safety zone. Individual vehicles in specific lanes along a given intersection approach, which have communicated to the IRI equipment their intended travel path through the intersection, will potentially be given different and distinct directives by the IRI than other AV fleet vehicles approaching the intersection but in different lanes and on different travel paths.

The way forward to achieving large-scale deployments of AV transport in automated mobility districts by 2030 envisions that multiple fleet operators, each with a different AV technology, will operate simultaneously throughout a specific AMD. With this common IRI roadway junction control system and an associated common response of each vehicle in each AV fleet to the IRI directives, the mixed AV and conventional traffic operations within the district will demonstrate substantial safety improvements over conditions without IRI deployment.

The IRI addresses a critical known operational issue with current AV demonstrations and deployments—that of left-turn movements across conflicting traffic at signalized intersections. Both AV deployments and many manually driven fleets avoid or minimize unprotected left turns, even at signalized intersections, in part because of the risk of opposing manually controlled vehicle traffic not yielding to traffic control. Such a hazard presents a significant safety risk, even for "protected green left-turn arrows" in today's signalized intersections. IRI has the capability to sense all traffic, detecting any vehicle that fails to decelerate in response to appropriate traffic signals. As such, the communication from an IRI-equipped intersection to an AV fleet can affirm safety of left-turn signals that no oncoming traffic is failing to yield, referred to as "safety-affirmative signaling and control." "Safety-affirmative control" reflects not just signaling red, yellow, and green, but also affirming that it is safe to proceed through the intersection based on IRI's active monitoring of all moving objects.

This concept of IRI applications aligns well with the principles of SAE J3216's definition of the level of prescriptive CDA. It is proposed that this safety-affirmative control functionality performed at IRI intersections will require each unique AV fleet technology to be designed to respond to the IRI command and control directives in exactly the same way as other AV fleets—a principle consistent with the safety protection provided by junction interlocking in automated guideway transit systems.

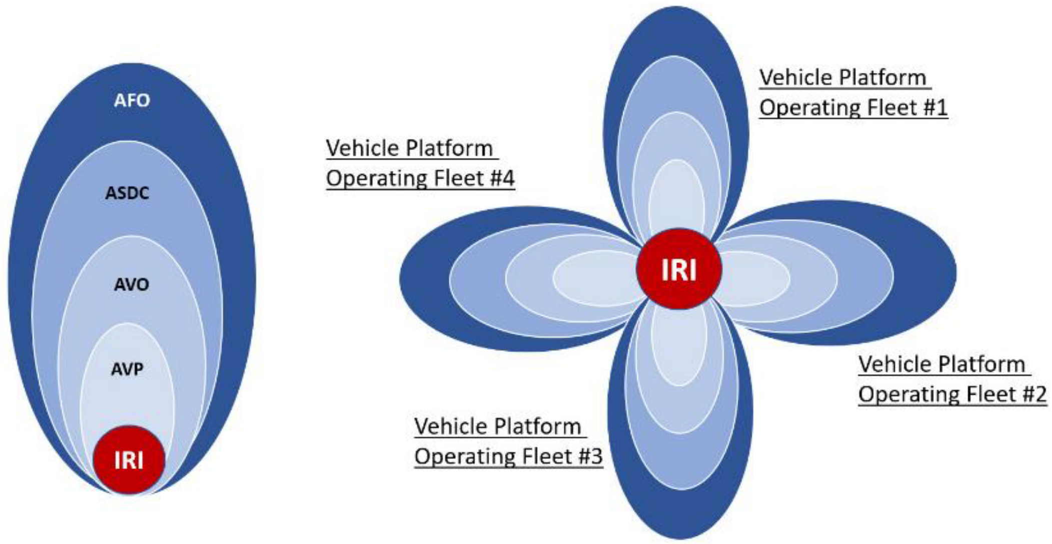


Figure 5-5. Districtwide roadway junction safety will be possible with IRI functionality when multiple AV fleets are designed to respond.

NREL is actively pursuing studies of ways traffic signal systems can help advance the conservation of energy, vehicle performance, and safety through the optimization of traffic operations. The illustration shown in Figure 5-6 has been developed to describe the range of functional purposes to which infrastructure perception and control can be applied to achieve such objectives. Improved safety is shown in the form of several functional aspects like adding protection for the green-yellow dilemma zone on approach and safety-affirmative signaling (which covers the IRI functionality discussed above for AV fleet vehicle protection). Another functional benefit of IRI is referred to in the figure as eco-approach/departure—aspects of controlling vehicle performance to minimize environmental impacts and energy consumption.

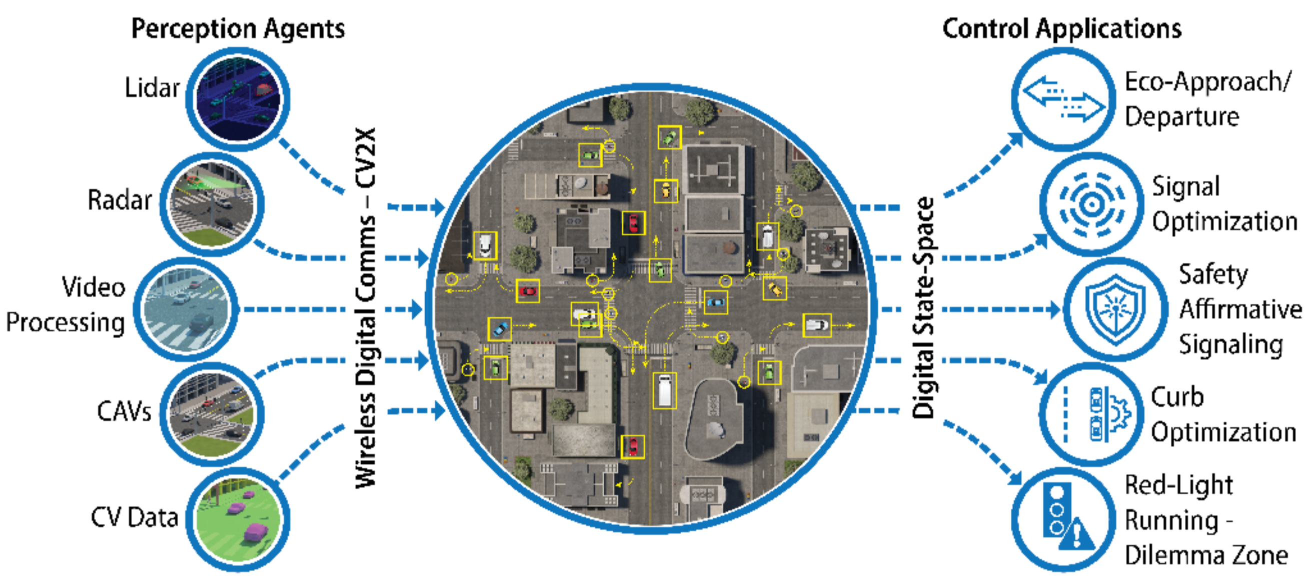


Figure 5-6. Multifaceted infrastructure perception and control can accomplish a number of operational IRI benefits.

Source: NREL

6 Next-Generation Traffic Control Technology: An Integral Part of AMD Implementation

Over the past 5 years, the experience gained at several operational sites that have deployed AV technology into mixed-traffic conditions has provided important insight into the problems that will be faced if AV fleet vehicles are left to their own sensing and perception capabilities. Section 1.3 addressed the essential need for applying control features at roadway junctions that serve to optimize traffic operations by improving the operating speeds and consistency of AV fleet vehicle performance within complex operating conditions. The application of CDA principles for vehicle-to-vehicle (V2V) sharing of information alone is insufficient for assuring and achieving maximum safety and operational efficiency in very complex operating environments. There is clear functional need for IRI coupled with traffic control and integrated with the AV fleet technologies to enable safe and efficient real-time response to dynamic traffic and pedestrian conditions. This will be referred to as the "next-generation traffic control system."

The reason this next-generation traffic control system will be critically important to AMD management authorities is that it will provide essential operational and safety benefits within a complex, mixed-traffic roadway environment. In particular, the use of advanced technology sensing and perception, with an associated command and control functionality at key intersections, will provide the capability to:

- Resolve issues of AV fleet vehicles slowing down on the approaches to complex intersections.
- Mitigate speed volatility of human-operated vehicles maneuvering to pass slow-moving AVs.
- Resolve 'seeing around the corner' issues, assessing cross traffic accurately, and mitigating hazards from human drivers who fail to yield right-of-way appropriately.
- Ensure each AV fleet technology does not have different operating speeds and protocols as complex traffic operations are encountered.
- Protect vulnerable road users moving within or across vehicle travel lanes.
- Ensure that the benefits of CDA are distributed as equitably as possible to all road users.

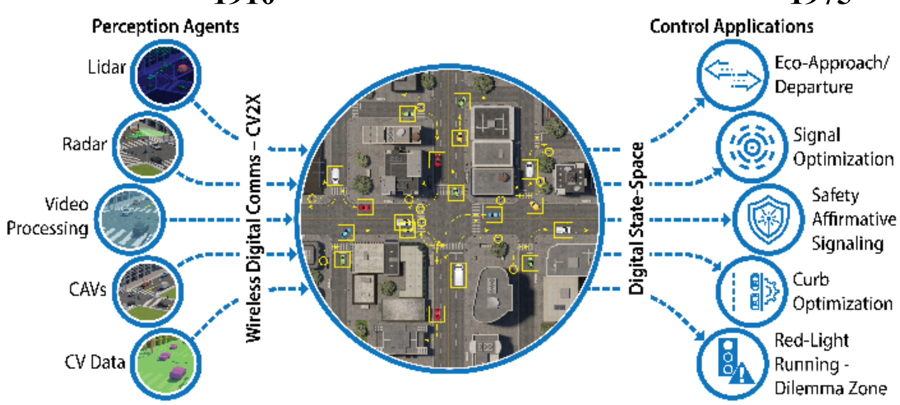
Conversely, without this infrastructure-based sensing and perception application to traffic control systems and the incorporation of the highest level of CDA prescriptive messaging, the insertion of AV fleet operations into the complexity of mixed-traffic conditions could cause:

- Continued, perhaps even escalated, traffic crashes at intersections, especially rear-end collisions by human drivers due to unexpected speed reductions of AVs.
- Inefficient operations with extensive speed perturbations and the related increased safety risks.
- Increased energy use and environmental emissions.

These factors reinforce the importance of the proposed AMD management authority that is responsible for traffic operations and the deployment of roadway infrastructure. It is proposed that the AMD management authority take the lead in implementing the evolutionary steps from today's signalized intersection traffic control technology to a new 21st century form—a path that will benefit the safety and efficiency of existing traditional modes, as well as enable near term

AV fleet adoption for public mobility. This evolutionary path contains changes to policy as well as technology. The responsibilities undertaken by the authority having jurisdiction will expand, as well as the technologies employed as part of the roadway infrastructure. This continued evolution from the early days of vehicle adoption is represented in Figure 6-1. A wholly new generation of traffic control systems will be required to accomplish this task between now and 2030.

1910 **1975**



2030

Figure 6-1. AMD management authority's deployment of the next-generation traffic control and signaling system will serve to protect roadway intersections for all roadway users and modes.

The safety analysis previously described by the management authority performed for each major roadway intersection/junction will determine the level of sensing required, the limits of the intersection domain, and active safety control to be performed by the intelligent infrastructure. This targeted safety case study will ensure the local intersection IRI is designed to direct AV fleet vehicles through the junction in a way that prioritizes safety for all modes.

With respect to the AMD management authority's liability arising from conducting safety case studies and subsequent deployment and operation of IRI, the management of such liability will also evolve from current traffic control management liabilities. Currently the city traffic department (or corresponding state department of transportation authority) is responsible and liable for the correct operations of traffic signals and the deployment of signage compliant with known standards and with the results of traffic control warrant studies. Likewise, responsibility, and corresponding liability, will evolve with the expanding role and responsibilities of an AMD authority. If traffic signal equipment, signage, curb drop-offs, etc., are contributors to a crash, the city/state/municipality is responsible and incurs liability to the extent that such engineering and operations errors contribute to the crash. This is evidenced by such entities occasionally being a party to associated lawsuits. However, since the predominant cause of crashes is human error, and the risk associated with modern traffic control equipment and traffic engineering is well managed, lawsuits against traffic jurisdictional authorities are rare. Even so, creation of an AMD management authority will increase exposure to such liability, though the evidence from existing practice indicates this will be a manageable risk.

Traffic signals are rarely part of the respective liability for crashes due to the high degree of fail-safe features built into the devices. But if the equipment fails in a manner not consistent with safety protocols, the responsible government would be liable, and would in turn pass that liability to the equipment manufacturer. The AMD management authority's safety case and its deployment of IRI technology would be designed in the manner of existing traffic signal system protocol, being "fail-safe" in its architecture when combined with the safety protection inherent in each AV vehicle's ADS, and the associated liability would work in the same fashion. Indeed, as the capability of IRI equipment increases and matures so as to be able to confidently detect a vehicle's failure to yield, it begs the question of whether liability is accrued if such information is not proactively shared and acted upon.

The level of various roadway users' activity will dictate any remediations needed through a safety case study, as well as provisions needed in sensing and traffic operational protections for:

- Conventional vehicles with human drivers.
- Pedestrians crossing the roadway travel lanes or gathering at multimodal junctions (e.g., AV transit station boarding platforms or curbfronts serving AV ride-hailing vehicles), including those in wheelchairs.
- Bicyclists in dedicated or mixed-traffic lanes, or crossing at an intersection.
- Micromobility users (e.g., skateboards, scooters, Segway transport).

Of equal importance to justify deployment of a next-generation traffic control system is to realize the benefits that go well beyond safety-affirmative control for AVs. These benefits address other important aspects of real-time traffic control and management for non-AV, and non-motorized roadway users. These benefits include:

- More efficient traffic flow with increased intersection throughput capacity.
- Increased safety from:
    - Early detection of failure to yield, allowing traffic control to attempt to pre-empt crash hazards through extension of all red.
    - Minimizing dilemma zones of approaching traffic.
    - Analyzing 'near-misses' to assess critical safety of intersections prior to crashes.
- Optimized energy management across all vehicular modes.
- Reductions of vehicle emissions.

Human-driven vehicles, pedestrians, etc. interacting with automated vehicles in AMDs create a level of complexity not found in even the most sophisticated, fully automated guideway transit systems that have been deployed around the world. With respect to safety, AVs are the most capable of predictable behavior via computer programming, in contrast to the human-driven vehicles and pedestrians that tend to behave more erratically. From this perspective, the IRI focus on improving the behavior of humans involved in transportation, with AVs as well as human-driven vehicles benefitting, is another significant objective of IRI. As such, an IRI investment strategy that creates a safer and more predictable roadway environment for all roadway users provides a greater return on investment of public dollars than an IRI that is focused only on AV operation, human-driven vehicles, or connected vehicle infrastructure alone.

In addition to increased safety and increased dynamic performance, IRI may include capabilities to optimize energy conservation and minimize environmental emissions (the “eco-approach and departure” at intersections). Intelligence to optimize signals by dynamically adjusting green and red signal timing to fit the traffic activity throughout the day simultaneously reduces travel delay, optimizes roadway capacity, and ultimately decreases energy use and emissions.

Near-term justification and return on investment of IRI will likely be focused on the significant safety, operational and energy/environmental benefits for human operated vehicles. These benefits accrue to traditional vehicles as well as advanced (though manually operated) vehicles equipped with V2I communication links with the infrastructure. For example, traditional vehicles as well as other road users will benefit from enhanced signal timing to lower delays and emissions. Similarly, all roadway users will benefit through enhanced safety from minimizing dilemma zones, as well as signal pre-emption (extending all red for example) in the event the system detects a vehicle failing to yield. Additional benefits will accrue to vehicles with V2I capabilities, whose onboard systems can further utilize the data coming from the IRI. This benefit will be amplified for those human-driven vehicles equipped with advanced driver assistance technology.

6.1 Fifth Cardinal Principle – Intelligent Roadway Infrastructure Is Integral to AV Fleet Operations and Management

This fifth cardinal principle addresses our premise that IRI will essentially become an integral part of the overall “system of systems” by which fleet vehicles safely and efficiently move through the roadway network when multiple AV fleets are deployed within an AMD. This integration and dependence is analogous to the role of existing traffic signal control to conventional roadway and vehicle operations. Modern multi-lane urban arterial corridors could not operate to any significant level of efficiency without coordinated traffic signals, pedestrian and vehicle sensing and actuation, and their corresponding management systems.

The next generation of traffic control technology is now in development, with extensive use of sensing technology, modeled after the technology applications for automated vehicle driving systems. The R&D for this type of sensor use is advancing toward practical application as part of roadway infrastructure.

Consider the illustration shown in Figure 6-2 of a roadway intersection where two arterial streets cross. Dedicated sensor stacks at each major intersection provide a real-time data feed to locally deployed processors performing artificial intelligence-based perception of the complete operating environment around that intersection. From this rich data source, the IRI signal system can perform safety-affirmative control that is specifically configured to guide multiple AV fleet vehicles through the intersection with minimal hazard exposure, and thereby also protects conventional vehicles, pedestrians, and micromobility road users at that specific physical intersection.

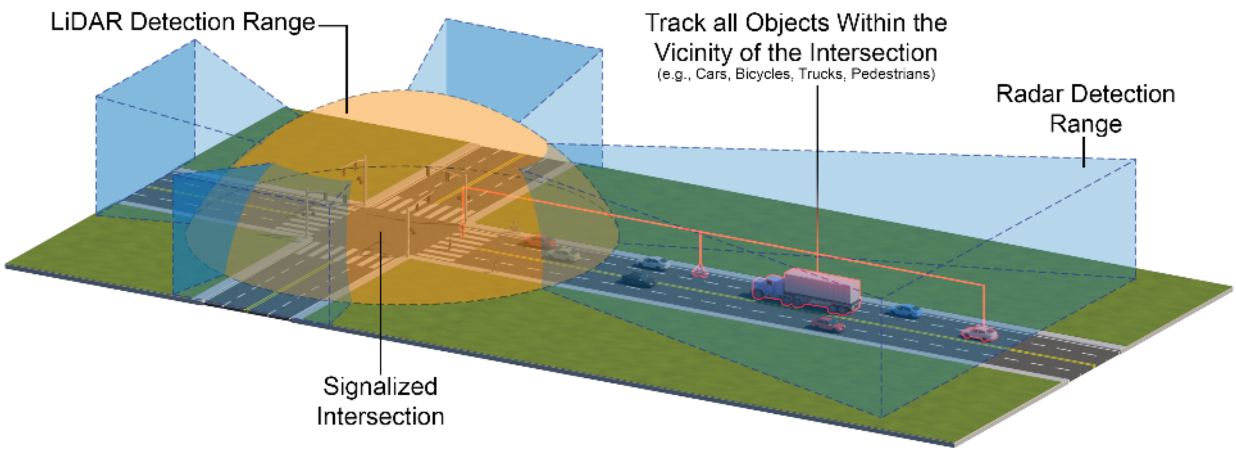


Figure 6-2. Next-generation traffic control has multiple sensors at IRI intersections.

Source: NREL

The concept and development of IRI is not unique to this research, as others are asserting similar concepts for intelligent roadway infrastructure specifically for protecting the operations of their individual AV fleet vehicles moving through roadway intersections, for the benefit general traffic operations, or for connected vehicle applications. The unique contribution of this discussion is the concept of a centralized, municipally controlled and administered IRI for the benefit of multiple applications including AV fleets, conventional traffic control, as well as many other applications in the automotive, roadway, and smart city space.

As discussed above, all of these functional control applications shown in the figure would involve the principles of cooperative driving automation, with the AV fleet vehicles responding to IRI directives at the highest level of what SAE J3216 calls "prescriptive CDA." In this approach, the AV fleet vehicles would be designed to defer to the safety-affirmative directives of the intelligent infrastructure.

One reality of "layered" control systems described by this Fifth Cardinal Principle does need to be addressed in the overall system design—that of system-level fallback operations at any time an IRI intersection enters a failure mode. When AV fleet vehicles are responding to a prescriptive command and control of a local intersection's IRI subsystem, and that specific intersection's higher IRI functionality fails to continue operating, the rest of the "system" must continue to operate—albeit in a "failure mode" of operations. This is analogous to what happens when failures occur at the "higher" subsystem levels of fully automated guideway transit systems—such as failure of the supervisory control subsystem. The precedent of guideway transit's automated control systems is that the automatic train operations can continue, but at a lower capacity and lower operational efficiency until the failed subsystem can be restored to operation.

This same principle of failure management applies to next generation traffic control based on IRI technology, which can and will fail on occasion—just as current traffic control occasionally reverts to all red flashing or goes dark due to power failures or other reasons. As with current traffic signal control, next-generation traffic control based on IRI technology will require fail-safe protocols so as not to induce crash hazards upon a localized failure. In the same way when an intersection's next-generation traffic control fails within an AMD, AV fleet vehicles would revert to solely in-vehicle ADS operation (as most currently operate now), and likely at reduced speed to ensure safe progression through the intersection at the expense of throughput capacity and efficiency of the roadway system.

To summarize, our premise is that this next generation of traffic control systems will be necessary not only for acceptable roadway junction operational safety, but also to ensure that the performance and capacity of urban arterial roadways with substantial AV fleet activity is sustained at the levels demonstrated today when all vehicles are human-operated, perhaps even increased. Further, our premise is that AMD management authorities must oversee large-scale, multi-fleet AV transport system deployments between now and 2030. For these AMD management authorities to be successful, it will be essential to deploy the IRI technology applications proposed here.

NREL is active in this space of technology application research that fosters the development of open-source sensor data processing and fusion shown in the future 2030 system in Figure 6-1, which illustrates the concept of a next-generation traffic control system (refer also to Figure 5-6 for figure details). NREL is also investigating the sensor fusion and machine learning technology required to perform the functional control applications shown on the right of this figure.

NREL is further researching not only the classic multimodal junctions at roadway intersections for application of IRI, but also other types of intermodal junctions such as locations where pedestrians enter and exit their AV transport vehicles, or where pedestrians need to cross AV pathways. This IRI deployment concept is particularly important for urban settings like those shown in Figure 6-3. These intermodal junctions can be in the form of busy arterial street curbfronts, larger AV transport passenger loading areas, and full-scale AV transit stations. New research initiatives are exploring the application of IRI for diverse AV transport services and modes, the findings of which are planned for inclusion in the next edition in the *AMD Implementation Catalog* series.

Figure 6-3. Curbside access to AV fleet vehicles providing ride-hailing services is another type of intermodal junction being studied by NREL for IRI applications in complex urban environments.

Source: Cruise. The Cruise Origin is expected to be deployed as an AV transport vehicle in San Francisco during 2022.

7. Summary of Findings, Conclusions, and Next Steps for Safe and Efficient AMD Implementation

This second edition in the *Automated Mobility District Implementation Catalog* has continued to document the progress, insights, and lessons learned from early-stage deployments of vehicle automation for the purpose of public mobility. During the intervening time since publishing the first edition, the number of players in the automated shuttle industry, as well as the automated vehicle industry overall, has experienced some attrition and consolidation, with the industry increasingly dominated by well-financed major players. Concurrently, NHTSA has acknowledged the emergence of an AV industry for which existing vehicle regulations and policy do not cover the eventual removal of the driver, and the corresponding unnecessary vehicle regulations such as a steering wheel and brake pedals. As a result, NHTSA has allowed exemptions for emerging AVs, but with restrictions.

With respect to AV shuttle operations, NHTSA now requires passengers to be seated and secured by seatbelts in response to an emergency braking incident in Columbus, Ohio, that caused minor injury. On top of these regulatory aspects was the emergence of the pandemic that not only minimized human contact in public places such as transit, but also diverted municipal, state, and federal resources toward pandemic remediation that may have otherwise been available for investments in innovations such as represented by AMDs.

Each of the 10 early-stage deployment sites have wrestled with both mastering vehicle automation and doing so in a complex environment in which other modes of transport coexist. This operational environment becomes particularly challenging at major intersections where conflicting movements of each of these modes must be safely managed.

Additional information on the conclusions summarized below can be found in Appendix B: *The Future of Autonomous Vehicle Transport in Automated Mobility Districts*. This appendix provides an overview of the technical papers and associated conference presentations that the authors have produced as foundational work preceding this second edition of the *AMD Implementation Catalog*. The content includes embedded links to video presentations on the NREL YouTube channel and to the summarized papers cited.

The following discussion identifies the key findings and conclusions of the research on AMD implementation as reported in this second edition.

Ten Early-Stage Deployment Sites – The majority of the 10 early-stage deployment sites have taken common steps to begin dealing with the complexity of an urban environment, either by choosing deployment sites and associated routes that minimize the complexity or, in limited cases, constructing infrastructure (e.g., bridges, crossing-arms, dedicated lanes) that assist in deconflicting and channeling various modes of traffic. Some are also evaluating aspects of infrastructure sensing and communication with the AV fleet vehicles. The 10 early-stage deployments share common approaches to development and deployment of their respective programs as public entities experimenting with new technology to provide improved public mobility. These commonalities are discussed below:

1. **Vision for the Future:** These early deployments were all part of a larger vision to eventually evolve and expand service to larger areas. Initial deployments were chosen to begin to understand and plan for a larger system.
2. **Phased Deployment:** Consistent with the above approach, early-stage deployments articulated foundational or incremental goals that would eventually build toward an integrated system.
3. **Adjustments for Unexpected Conditions:** Understanding the pioneering aspect of these initiatives, these deployments were typically flexible and nimble in responding to unexpected technical glitches or changes in policy or regulatory oversight. Indeed, most encountered and had to adjust to either technical, administrative, or regulatory disruptions to their plans.
4. **Partnership Essential for Progress:** Each early-stage deployment formed essential partnerships with AV developer(s) and other industry players to continue progressive technology advancement, including securing funding, establishing contractual relationships, and reconfiguring partnerships/relationships as some companies leave the pursuit.
5. **Improved Equity of Access:** Improved access equity leading toward high-quality mobility for all passengers, including the elderly and the disabled, was a common theme across deployments.
6. **Challenge of Preparing for Mixed-Traffic Operations:** Each deployment continued to press toward meeting the challenge of fully automated Level 4 operations in mixed-traffic conditions with no operations personnel required to be on board the vehicles with passengers.
7. **Extended AV Service Within the City:** The ambition for each early-stage deployment site was to extend the benefits of automated mobility beyond the early deployment site to reach larger areas, particularly **the urban core of the city**—and for some, also providing connections to regional high-capacity transit.

Safety of operations was the overriding guiding principle in each early-stage deployment. Common approaches to mitigating hazards were to decrease vehicle speed whenever potentially hazardous conditions were detected, as well as utilizing a safety driver or attendant to take control in highly complex situations. As a result, typically in complex situations involving mixed traffic, the vehicle would slow down—many times to unreasonable speeds in relation to the surrounding traffic—while waiting for its automated control system to determine when it was safe to proceed, or to yield control to a manual operator.

The one exception to this was the European deployment in the Rivium office park, which has for 20 years employed segregated infrastructure (a dedicated bridge, protected operating paths, and pedestrian and vehicle crossings equipped with crossing-arms) to isolate the shuttle vehicles from other modes. However, such investment in parallel infrastructure is cost-prohibitive, and even the European deployment is seeking to extend service on existing roadway infrastructure without extending the existing dedicated infrastructure.

Another common challenge of early pilot projects has been accessibility for the disabled population in accord with ADA regulations. The challenge comes when addressing these policy goals while still keeping the ADS technology development moving in incremental steps, and while keeping the vehicle design simple and efficient.

Even with these hurdles, much has been learned over the past 5 years of early deployment. There is a growing body of knowledge about how AV technology will fit into the urban transportation landscape, and what needs to change in AV technology design and capabilities to integrate well into dense urban settings.

In each of the early-stage deployments, "managed fleet operations" were employed in which a supervisory control system allowed for operational monitoring from a remote command center, even in operations with a single vehicle in passenger service. Fundamentally, the supervisory subsystems are designed to allow the system to scale up as vehicles are added to the fleet operation and as the service area is expanded over time. Such supervisory control system frameworks for fully automated transport systems have been well established, having evolved from the last 50 years of industry design of automated people mover systems such as those common in large airports, and in the last few decades even regional-scale automated fixed-guideway mass transit systems.

Another commonality for many deployment sites is system-level management by an independent fleet operator. In several of these early-stage AV deployments, the day-to-day management and operation of the system is contracted through operating companies that are experienced in operating conventional public transit systems.

Multimodal Environment – Research and development work in the industry has focused on the objective of deployment within mixed traffic, in which the AV fleet vehicles would be operating among conventional vehicles with human drivers. This is the first level of operational complexity to be dealt with beyond Avs operating in dedicated and semi-protected lanes.

Vehicles under human control are already accustomed to traditional traffic control with its associated signaling. Any intersection control that better accommodates automated vehicles must also accommodate (and perhaps improve) legacy signaling operations, as well as anticipate the high occurrence of manually driven vehicles that fail to yield to that signaling. Currently, automated vehicles confronted with a busy and complex roadway junction need to reduce their approach speed to maintain safety by providing additional time to process data from multiple sensors and execute decisions within the dynamic driving task. AVs operating at low speeds in mixed traffic have been found to aggravate human drivers, who in turn are more likely to aggressively overtake these slow-moving vehicles, resulting in greater speed volatility within the traffic flow.

The AV operating environment is now also being assessed in terms of the increased complexity when vulnerable roadway users interact with traffic in dense urban areas. Findings with regard to these users are summarized below:

- Pedestrians: This includes pedestrians crossing the roadway travel lanes at intersections or pedestrian crossings. It also includes pedestrians gathering at multimodal junctions such as at AV or conventional transit stations, as well as curb fronts serving AV or conventional ride-hailing vehicles and other mobility services. Pedestrians are the most vulnerable of road users, and accommodating their crossing patterns as well as boarding/alighting at multimodal junctions in close proximity to the AV travel lanes presents further challenges for automation. Ultimately, safe AV operation will require machine intelligence to distinguish normal pedestrian behavior from that which presents a potential collision hazard.

- Bicyclists: People riding bicycles—whether in dedicated or mixed-traffic lanes or crossing at an intersection—add further complexity of the roadway due to their travel speed and ability to suddenly change direction. With the electrification of bicycles, ridership is showing to be more prevalent as it appeals to a larger demographic.
- Micromobility: People using skateboards, scooters, Segways, and various other emerging, electrified modes are becoming very common in urban districts. Like pedestrians and cyclists, the relatively low mass of micromobility makes these roadway users highly vulnerable in the event of crashes, and the electrification of such devices makes their movements even quicker, more agile, and somewhat more unpredictable compared to traditional pedestrians and cyclists.
- Transit: Both buses and light rail transit add to the complexity of the roadway, as do the boarding stations when integrated into a dense roadway environment.

A primary conclusion drawn from these early-stage deployments is that navigating this complex operational environment will require further advances in sensing and artificial intelligence perception technology. Ongoing research sponsored through the U.S. Department of Transportation and other institutions is being structured to assess how advanced sensing and control technology might be applied equally to the roadways, as well as to the vehicles themselves, in order to achieve robust, resilient, and fail-safe operation. Such technology applications, referred to in this document as "intelligent roadway infrastructure," provide the requisite intelligence to enable next-generation traffic control operations to safely allow these multiple modes to share the right of way. Next-generation traffic control through IRI concepts are being pursued to improve existing traffic control (increased safety and decreased delay and energy use), to become an active part of the evolving connected vehicle architecture, and to enable various smart city applications, in addition to enabling 'safety affirmative signaling' as discussed herein.

At roadway junctions, in particular, IRI technology can adequately deconflict turning movements at intersections while allowing the AVs with which it is communicating to maintain acceptable speed and performance as they approach the junction. IRI provides effective means (as well as redundancy) to see around corners, effectively assess cross traffic, and to determine if any approaching vehicle is failing to yield right-of-way—forming the basis of "safety affirmative signaling." IRI is a component of the "system-level" view of automated mobility that is espoused in this document—a system that is larger than just the individual vehicle fleet and its automated control technology. The system espoused is in reality a "system of systems," encompassing the overall automated mobility system within an AMD that wraps around both the individual fleet vehicle technologies and the roadways as well, and that integrates with traditional traffic control and its associated modes. Implementation of IRI may initially focus on challenges and safety of human driven traffic, but ultimately will form the basis for safety of multiple AV fleet services at critical, complex junctions within an AMD.

<u>Large-Scale Deployments Will Require Intelligent Roadway Infrastructure</u> – A significant percentage of early AV deployments have relied on some form of roadside infrastructure to sense some aspect of the dynamically changing road environment when the automated vehicles move through mixed traffic. Other sites are preparing to apply the advanced technology to infrastructure in the coming phases of research and development.

The continuous communication of information about these dynamic conditions to the AV fleet vehicles as they approach roadway junctions typically is designed to protect the vehicles and their occupants in complex conditions where there is a convergence of other conventional human-driven vehicles, pedestrians, and active transportation roadway users, or combinations of these modes. Applications of intelligent roadway infrastructure integrated as a part of the AV fleet's operational control system have been observed or noted in the latest phases of several deployment sites. Observed integration of IRI included such things as traffic signal phase and timing, operational states of other vehicles, and presence and proximity of pedestrians and other vulnerable road users such as cyclists and micromobility.

Although technical progress is being made to enable AV public mobility fleets, AV developers are sending signals that there still needs to be limitations to the complexity of operating conditions, combined with a realistic lowering of expectations for what an individual automated vehicle can do when operating in dense urban settings. One observed approach is to restrict the ODD of the system to a prequalified set of routes or roadways—particularly routes that limit, or even prohibit, left-hand turns across oncoming traffic. Whereas previous AV shuttle descriptions point to a geofenced service area, more and more demonstrations are restricting operations to a defined and restricted roadway network within the geofenced area with limited stations/stops, referred to as a "geo-net." A carefully constructed geo-net minimizes operational complexity, maximizing safety and reliability of the system. A geo-net approach combined with IRI at critical roadway intersections forms a path to continued progress toward safe effected AV fleet performance for public mobility applications.

<u>Integration of IRI Technology Within AV Control Systems</u> – The integration of real-time data from IRI to support AV deployments at full scale points to a growing acknowledgement from AV public mobility developers that IRI will be required, particularly in complex urban environments. This is also supported and acknowledged by SAE International for general AV technology deployments through the concept described in SAE J3216—that of "cooperative driving automation." CDA defines four levels beginning at status-sharing, progressing to intent-sharing, then agreement-seeking, and finally prescriptive actions with the intent of enabling cooperative driving through the various SAE defined levels.

Based on the findings and observations of early AV deployments described above, and on the tendency toward geo-net operation and emerging principles of cooperative driving automation, the inference drawn is that this additional infrastructure roadway intelligence (this next generation of traffic control) will be necessary to integrate into the AV fleet operational control systems to ensure safety and operational performance, particularly at complex junctions. Note that IRI is not mandatory for operations in less complex environments, relying on the intelligence of the vehicle to traverse a confined geo-net. At complex junctions, IRI will create and disseminate a verifiably accurate digital representation of all movement within the sensing field of view. Such advanced technology infrastructure will be essential to improve existing traffic signal control, enable CDA, and achieve near- to medium-term implementation of fully automated public mobility systems within large, operationally complex urban districts and major activity centers. This IRI functionality will provide the necessary redundancy for fail-safe operations in the form of safety affirmative signaling while allowing AVs to maintain a high level of performance.

This development of next-generation IRI-based traffic control should encompass several objectives if the creation of automated mobility districts in the form described are to be realized in the near to medium term:

- Resolving the issue of slow-speed AV approaches to complex intersections.
- Mitigating speed volatility of human-operated vehicles maneuvering to pass slow-moving AVs.
- Resolving 'seeing around the corner' issues, assessing cross traffic accurately, and eliminating hazards from human drivers who fail to yield right-of-way appropriately.
- Ensuring each AV fleet technology operating within an AMD does not have different operating speeds and protocols as complex traffic operations are encountered.
- Protecting vulnerable road users moving within or across vehicle travel lanes.
- Ensuring that the benefits of CDA are distributed as equitably as possible to road users.

Intelligent roadway infrastructure provided within a cooperative driving environment would help mitigate the safety and efficiency issues presented by mixed-traffic conditions with human-operated vehicles, while providing safety and efficiency benefits to all road users. These issues are particularly relevant to mitigating traffic accidents at intersections—especially rear-end collisions caused by conventional human-driven vehicles hitting slower-moving automated vehicles. IRI applications will also help resolve inefficient operations with extensive speed perturbations by human-operated vehicles and the related increased safety risks due to failure to yield at signals and rear-end collisions from these speed differentials, as well as the increased energy use and environmental emissions resulting from speed perturbations. Indeed, these latter issues may lead the adoption and deployment of IRI in the near-term as manually driven vehicles will dominate traffic for many years to come.

AMD Management Authorities Essential for the Future – The definition of an AMD management authority can be viewed as a corollary to the deployment of IRI, which enables multiple AV fleets to operate safely and efficiently with manually driven vehicles and other modes. Such an authority may evolve as an extension of current city department of transportation responsibilities or may be specially designated through legislation. An AMD management authority has legal jurisdiction to oversee transportation policy, operations, and the associated infrastructure to ensure safety, efficiency, and performance of an AMD. Creation of such an authority will provide the larger management structure necessary to implement the "system of systems" operational concept for large-scale AV deployments. Designation of such an authority will be necessary for closed campus AMD application, or within the geo-fenced region of public mobility AV fleets. Whether an evolution of a prevailing roadway authority or the creation of a specific and separate authority for this purpose, the AMD management authority will require the requisite talent, resources, and financial capability to support AV deployments with respect to safety audits, deployment of infrastructure, and development of policy relative to an AMD.

Among other things, the AMD management authority would prescribe the operational rules for failure response with regard to AV fleet vehicles in the form of both individual vehicle fallback actions, as well as the failed-vehicle recovery protocols to be followed by the respective AV fleet manager's operations staff. The jurisdictional authority's rules and protocols would determine how and where a failed vehicle should come to an acceptable stop to minimize traffic flow disruptions, as well as guidelines to execute recovery.

Such a management authority has precedent with roadway traffic control as demonstrated by existing local entities having jurisdictional authority to develop and operate traffic with respect to speeds, signage, and traffic signal systems. Municipalities are typically responsible for traffic warrant studies, as well as signal timing and various other intersection control. The Houston Uptown district is an example urban area overseen by one such quasi-governmental district management authority. The Uptown Management District was given jurisdiction by the Texas legislature to oversee complex integration of various transportation modes and to deploy any associated infrastructure to accomplish that goal, in coordination with the City of Houston. Uptown also has the legal authority to levy a 15 cent per $100 assessed value ad valorem tax on properties within the district boundaries as revenue used to finance such improvements. A similar authority is needed for AV integrated operations when a district is applying the "systems of systems" approach to management of multimodal operations.

Five Cardinal Principles – In summary, the lessons derived from the 10 early-stage deployments of AMDs, combined with inferences from decades of precedence and experience with automated transit systems and traffic signal systems, have been synthesized into five cardinal principles that typify what is believed to be necessary to enable and deploy fully automated mobility systems in the near term:

First Cardinal Principle – A dense urban setting is important for an AMD

An AMD reflects a spatial area of significant trip demand that is poorly served by privately owned vehicles and traditional transit, and is therefore desirable to improve public mobility by providing services based on AV technology. Examples of this include dense urban districts and major activity centers such as educational, medical, and business campuses. Such settings are conducive to the application of AV-based public mobility services due to the concentration of trip-demand, yet they also present some of the greatest challenges due to density and variety of competing modes creating a complex operating environment. Although there are opportunities for productive AV deployments apart from AMDs, such as small-town circulators, freight, first-last mile, and corridor applications, dense urban districts and other potential AMD sites present greater societal benefit and return on investment by concentrating these mobility services within a relatively small and dense geographically bounded area. But with these application benefits also come some of the greatest challenges to effective implementation.

Second Cardinal Principle – Independent fleet operators and multiple AV technologies will likely be deployed in an AMD

AV technology for public mobility will be primarily deployed in managed fleet operations over the coming few decades, and it is highly likely that multiple automated fleets will be active in any given urban district. These fleets may be competitive and/or complementary with some focusing on public mobility services such as first-mile/last-mile, internal district circulation, fixed-route, or on demand, and others on freight/cargo and package delivery. As such, management of AMDs need to consider and accommodate both legacy non-automated modes (traditional vehicles, transit, pedestrian, bicycle and micromobility), as well as potentially multiple automated modes.

Third Cardinal Principle – A management authority is a necessity for an AMD

Whether an evolution of existing traffic jurisdictional responsibilities, or by designation of a new authority through legislation, management of an AMD will encompass both policy and operational responsibilities needed for efficient AV fleet operation in addition to enhanced traditional traffic operations. Precedent for such an authority is well established with current traffic laws, jurisdiction, and enforcement. While current traffic control is quickly evolving with more advanced spatial sensing, connected vehicle infrastructure, and cooperative driving automation, AMD management will further require implementing AV policy, deploying infrastructure, and enforcing AV safety guidelines for the benefit of the traveling public.

Fourth Cardinal Principle – Intelligent roadway infrastructure is needed at complex multimodal junctions

The transition to more intelligent intersections is occurring now. Next-generation traffic control will deploy intelligent roadway infrastructure to provide a complete and accurate "digital twin" of the location and movement of all roadway users. Such intelligence is necessary to safely manage the complexity of roadway traffic through major junctions such as arterial street intersections, improving the safety of current human driven traffic safety as well as enabling safe and efficient AV fleet operation. AMD management authorities will need to deploy such infrastructure in order to safely manage AV fleet operations by affirming safety of signalized turning movements and alerting any connected roadway user (whether automated or not) of impending hazards from vehicles that fail to yield.

Fifth Cardinal Principle – Intelligent roadway infrastructure is integral to safe AV fleet operations and management

Intelligent roadway infrastructure deployed and managed by AMD management authorities will be an essential and integral part of the overall "system of systems" to guarantee full system safety. AV fleet vehicles that are cooperative with IRI prescriptive communications will be enabled to 'see around corners', assess cross street traffic, and confidently make turning movements while avoiding the hazard of human drivers failing to yield. When appropriately integrated with IRI, each fleet's vehicles may safely and efficiently navigate complex roadway junctions without undue decreases in speed, eliminating dangerous speed perturbations. The next generation of traffic control technology is now in development, with extensive use of sensing technology targeting both enhanced safety and decreased travel time benefits of traditional traffic, as well as enabling various applications for connected and automated vehicles. Within AMD districts, such technology will not be just complementary, but essential and integral to the safe operation of AV fleets for public mobility.

Next Steps for AMD Implementation Research – The next steps in this AMD research effort will continue to focus on tracking the substantial research and development necessary to implement the above, as well as identifying and assessing emerging issues that require attention and subsequent analysis. These emerging issues include the following:

- Private deployments of AV fleets: All 10 early-stage deployments were public-led or highly public-coordinated efforts with private partners. Transportation network services with AV-operated vehicles are beginning to be deployed in the United States, such as those in Chandler, Arizona, and San Francisco, California, as well as in a few locations abroad. Moving in parallel with public AV mobility deployment, but private in nature, these private companies are also pushing the boundaries of AV mobility. Even as private initiatives, these deployments require consent of the associated municipalities, as well as enabling policy to allow Level 4 vehicle operation. As private entities not managed by a public entity, information on these initiatives is less transparent, but still critical to understand the entire evolution of public mobility through AVs. The next edition will include related private initiative site deployment examples and, to the extent possible, critical insights and lessons learned.
- Passenger boarding and alighting processes and associated station operations: The stations where passengers board and alight the AV fleet vehicles may prove to be the critical capacity constraints for high-demand areas, as it is a primary limiting factor for current fixed guideway mass transit systems. Appropriate design and operations principles and station configuration schemes need to be understood to maximize performance of the system. Furthermore, as most of the AV deployment concepts are transitioning toward electrified powertrains, integrated electric vehicle charging within stations will also be critical to support an efficient duty cycle of the fleet.
- Standards and open-source data interfaces: Although standards are moving forward with respect to vehicles, the overall framework for managing multiple AV fleets to enable AMDs goes beyond vehicles to that of a "system of systems" framework. Principles and standards, many of which are conceptually explored in this report, need codification by broad government and industry representation through one or more appropriate standards-setting organizations.

In order to leverage AV fleets for public mobility in the near term, an effort should begin now to develop the technology needed for infrastructure sensing, perception, and control, providing affirmative safety traffic control for AV fleet vehicles in particular, and for all modes and roadway users in general. If the transportation industry is to be fully prepared in 5 to 10 years to meet the challenge of multiple AV fleets operating in our dense urban centers, the industry needs to aggressively pursue the development of this new intelligent roadway technology within automated mobility districts. This effort will entail the cooperative design, test, and development of such technology across industry, government, and local jurisdiction authorities to ultimately achieve the vision of fully automated, unmanned AV transport deployed on a large scale in our urban centers.

Appendix A. Typical NHTSA Stipulations for a Box 7 Importation and Approval for Site Operations

Source: NHTSA March 17, 2020, Authorization Letter to TransDev for Site #9 Gainesville, Florida Phase 2 Deployment

NHTSA has reviewed your application to use the Vehicles in the research and demonstration program, and is granting your request subject to the following conditions:

1. This grant of permission applies only to the Vehicles identified above in the research and demonstration program described herein. If you seek to import or use any additional nonconforming vehicles for testing or demonstration purposes, regardless of whether they are the same model as the one that is the subject of this letter, you will need to separately request and receive permission from NHTSA prior to importation or operation.
2. The Vehicles' entry and presence in the United States must be in compliance with all U.S. Customs and Border Protection ("CBP") requirements.
3. The Vehicles may only be operated with a trained safety operator on board who, at all times, is in physical possession of the control module so that he or she can take immediate control of or stop the Vehicle should the need arise. If worn, the control module must be tethered to the safety operator in a manner as to restrict its freedom of movement to prevent injury during a sudden stop.
4. The Vehicles must be configured in such a way to allow movement, in either autonomous or manual mode, out of the path of vehicles, pedestrians, and obstacles. The safety operator must have a means to take control of the Vehicle at any time to move it to a safe location.
5. The Vehicles must allow the safety operator to activate a horn or other audible warning at all times. The horn or other audible warning must be capable of emitting continuous and uniform sound audible under normal conditions from a distance of not less than 200 feet while activated.
6. The Vehicles and their operation must comply with all federal, state, and local laws and requirements at all times. Each vehicle must be duly permitted, if applicable, and authorized to operate within all properties and upon all roadways traversed by the route in the manner and conditions described herein.
7. The Vehicles may not be operated in adverse weather and road conditions, which include heavy precipitation, such as heavy rain, heavy snow, fog, or hail; humidity greater than 95%; sustained wind speeds greater than 31 mph; or temperatures below 0 °F (-17.8 °C) or above 95 °F (35 °C).
8. No more than two of the Vehicles may be operated on the route described above at any given time.
9. Before operating the Vehicles under any conditions other than those specified in this permission letter, you must, as applicable in subparagraphs (a) and (b) below, either request and receive permission from NHTSA or notify NHTSA before making any changes. For purposes of this permission, a change in conditions should be broadly

construed to include any alteration of the conditions, vehicle operation, or route described in this letter, regardless of whether such a change was instituted by you or a third party, such as a modification of the roadway design.

A. If any such change in condition relates to public road operation or to any operation that involves members of the public[23],1 you must **request and receive permission** before operating under such changed conditions. Please allow at least forty-five (45) calendar days for NHTSA to respond to requests to change operating conditions.

B. If the change solely involves operation of the Vehicles off public roads without interaction with members of the public, you must **notify** NHTSA via email at least seven (7) calendar days prior to making any of the desired changes. Such notifications and requests must be submitted to ___.gov and include complete details about the changes.

10. The Vehicles must be equipped with the following:

A. Seat belts at each seating position.

B. Audible alerts warning passengers that the vehicle is a research and demonstration vehicle that may stop suddenly and of the need to fasten their seat belts.

C. Software version ___ or later.

11. Apart from the safety operator, standing passengers are not permitted while operating the Vehicles with members of the public on board.

12. The Vehicles must display the following labels formatted in a manner that can easily be read and be located in a place that is readily visible:

A. A label or labels, affixed to the interior and exterior of the vehicle, warning prospective and actual occupants that the vehicle does not comply with all applicable Federal motor vehicle safety standards.

B. A label or labels, affixed to the interior of the vehicle, warning occupants that the vehicle is a research and demonstration vehicle that may stop suddenly and of the need to fasten their seat belts.

C. A label or labels, affixed to exterior of each vehicle, warning other road users that the vehicle may stop suddenly.

13. Safety operators must be regularly trained and monitored. All safety operators shall receive specific training on passenger safety and emergency response scenarios. Operator performance monitoring shall occur at least as frequently as described in your application dated ________.

14. You must notify NHTSA whenever any of the Vehicles is involved in a crash, near miss, or any other situation in which it posed a risk to the safety of any individual(s), whether

[23] For purposes of this letter, "members of the public" includes anyone that is not employed by (or is an agent of) either the manufacturer or importer of the subject vehicle. To the extent an educational institution is included as a stakeholder in any such demonstration program, "members of the public" includes students of the educational institution.

such individual(s) were inside or outside of the Vehicles at the time of the incident. These include, but are not limited to, situations in which the safety operator acted to avoid an imminent crash, instances in which the Vehicles deviated from the prescribed route, unexpected lane departures, and any situations that resulted in injury to vehicle occupants, pedestrians, bicyclists, or occupants of other vehicles. You must provide notification of the incident and a full description of the occurrence within twenty-four (24) hours of the event. When applicable, copies of all accidents report(s) concerning the occurrence prepared by State or local law enforcement authorities must be provided within five (5) business days of when those reports become available.

15. You must submit a monthly report to NHTSA on the 15th of each month listing all unplanned disengagements[24] occurring during the previous month during operation of the Vehicles that involves interaction with the public[25]. The report must include a description of the event(s) that triggered the disengagement, including, how any pedestrians, vehicles, or other objects were involved, as applicable. The report must also include the date, time, location, weather conditions, and speed immediately prior to disengagement. Further, the report must list the ADS software version, the total number miles accumulated in the reporting period and, separately, the number of miles accumulated with the Autonomous Driving System engaged. The report must be emailed to Box7imports@dot.gov and should have a subject line containing "______", "Disengagement Report", and "[VIN]."

16. You must provide NHTSA with documentary proof that the Vehicles have been exported or destroyed not later than thirty (30) days following the end of the period for which it has been admitted to the United States. Please note that failure to provide acceptable proof of export or destruction can result in the denial of future applications.

17. You must submit an annual report to NHTSA on the status of all vehicles imported by you with active permissions as of the date of the report. The report should identify, by vehicle identification number (VIN), all vehicles that remain in the United States. The report should also identify all vehicles removed from service, the reasons for their removal, and their disposition. The report must be emailed to Box7imports@dot.gov and should have a subject line containing the words "_______", "AVEP Annual Report", and the year.

18. The vehicle must be made available for inspection by NHTSA upon request.

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[24] For purposes of this condition, an "unplanned disengagement" includes but is not limited to instances when the Automated Driving System deactivates or the vehicle test driver disengages the Automated Driving System and takes manual control of the vehicle, for any reason, at times or locations not pre-planned in the route, or when a passenger disengages the Automated Driving System.
[25] For purposes of this condition, "interaction with the public" includes operation on public roads, operation near members of the public, or the use of the vehicle to transport members of the public.

Appendix B. The Future of Autonomous Vehicle Transport in Automated Mobility Districts

This is an overview presentation of the research performed on automated mobility districts (AMDs) from 2019 through 2021 by the Mobility Innovations and Equity team at the Center for Integrated Mobility Sciences at the National Renewable Energy Laboratory (NREL) in Golden, Colorado. The general topic addresses "What we have learned over the last 5 years and what we must prepare to do over the next 5 to 10 years" with respect to the full-scale deployment of automated/autonomous vehicle (AV) technology transport in dense urban settings—defined as automated mobility districts (AMDs).

This overview is provided as a 15-minute executive summary presentation and a full 40-minute presentation on the NREL Learning YouTube channel through the following links:

- The Future of AV Transport in Automated Mobility Districts - Executive Summary
- The Future of AV Transport in Automated Mobility Districts

Abstract

This presentation highlights the insights from ongoing research and looks forward with a broad view of how automated mobility will be deployed in dense urban environments over the coming decades. In particular, the role of intelligent roadway infrastructure is explored as the next generation of traffic control and management technology, with analogies to communication-based train control that has seen decades of proof and experience. The presentation addresses how far we have come in the last 5 years of AV research and development and considers the road ahead as the industry moves from demonstration pilots to full-scale deployments. The realities of multiple AV fleets operating under the control of different fleet managers within the boundaries of a large urban district or major activity center are considered, and the proposed direction needed for an AMD management authority is identified. The specific role of an AMD management authority is to hold the jurisdiction over safe traffic operations and the related deployment of intelligent roadway infrastructure. The larger benefits are discussed in terms of a safer environment for all modes, including human-operated vehicles, pedestrians, and active transportation, as well as more efficient traffic operations, reduced energy use, and mitigated environmental impacts. Finally, a series of conclusions are drawn from the overall research findings to date.

Additional NREL Presentations on This Topic

Supporting this overview presentation are two more detailed presentations that were originally presented at industry conferences in 2021. These presentations are also accessible through NREL's YouTube channel, with the following topics and technical reference information:

- "Safe Operations at Roadway Junctions – Design Principles from Automated Guideway Transit"
    - Presentation (25 minutes): https://www.youtube.com/watch?v=6zFDBfbRWHo.
    - Coauthors: J. Sam Lott, Stanley E. Young, and Lei Zhu.

- Technical paper and presentation at the SAE International/Association for Uncrewed Vehicle Systems International 2021 *Business of Automated Mobility (BAM) Forum* [1].
    - Selected by SAE as one of the best papers at the BAM Forum and chosen for publication in the 2022 *SAE International Journal of Advances and Current Practices in Mobility* [1].
- "A Safety and Management Framework to Enable Automated Mobility Districts in Urban Areas"
    - Presentation (25 minutes): https://www.youtube.com/watch?v=jbH02L_bpXI
    - Coauthors: J. Sam Lott and Stanley E. Young
    - Technical paper presented at the ASCE 2021 *International Conference on Transportation and Development* [2].

Citations:

1. J. Sam Lott, Stanley Young, and Lei Zhu. 2021. "Safe Operations at Roadway Junctions - Design Principles from Automated Guideway Transit." *SAE International Journal of Advances and Current Practices in Mobility* 4 (1): 260–269. https://doi.org/10.4271/2021-01-1004.

Abstract

This paper describes a system-level view of a fully automated transit system comprising a fleet of AVs in driverless operation, each with an SAE Level 4 automated driving system, along with its related safety infrastructure and other system equipment. This AV system-level control is compared to the automatic train control system used in automated guideway transit technology, particularly that of communications-based train control (CBTC). Drawing from the safety principles, analysis methods, and risk assessments of CBTC systems, comparable functional subsystem definitions are proposed for AV fleets in driverless operation. With the prospect of multiple AV fleets operating within a single automated mobility district, the criticality of protecting roadway junctions requires an approach like that of automated fixed-guideway transit systems, in which a guideway switch zone "interlocking" at each junction location deconflicts railway traffic, affirming safe passage. The analogous AV protection safety subsystem is defined as fail-safe equipment that monitors roadway intersections and junctions, communicates traffic signal status, perceives and communicates alerts and signals to AV connected vehicles concerning potential unsafe conditions, and performs related primary safety functions. Conclusions are drawn that the AV protection roadway intersection functions must be performed by local roadside equipment dedicated to protecting each roadway intersection and junction. Further, it is concluded that the communications technology connecting the infrastructure with the vehicle to perform this vital, fail-safe protection should meet specific functional and performance criteria.

2. J. Sam Lott and Stanley E. Young. 2021. "A Safety and Management Framework to Enable Automated Mobility Districts in Urban Areas." Presented at the *International*

Conference on Transportation and Development, 8–10 June 2021. https://doi.org/10.1061/9780784483534.045.

Abstract

Automated mobility technology is beginning to emerge as a viable means to create sustainable and effective public mobility systems within denser urban environments. Automated mobility districts describe major urban districts or activity centers in which deployments of multiple automated vehicle transit and ride-hailing fleets are supported to meet public mobility needs. The authors put forward a framework to enable AMDs and their governing and management jurisdictional authorities to manage safety of AV operations based on lessons learned from the last century of automated guideway transit and roadway intersection traffic control systems. The essential concept is that of operational management and safety-critical control of multiple AV fleets using a "system-of-systems" approach to system safety analysis. The safety analysis would focus on safe passage of the AV fleet vehicles through complex roadway intersections and junctions, especially in the presence of other non-automated modes such as pedestrians and manually operated vehicles.