Scan and Review of Autonomous Shuttle Operation and Other Personal Transportation Options Affecting Autonomous Transit Viability

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Final Report

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The opinions, findings, and conclusions expressed in this publication are those of the authors and not necessarily those of the State of Florida Department of Transportation.

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16. Abstract

At the state and national levels, there is continued interest in AV technologies and in providing a broad set of transportation options. Furthermore, technologies such as mobility on demand, ridesharing, and micromobility provide alternative options. Research is needed to understand how AV shuttles and other advanced technology-based options may offer solutions to the transportation challenges faced by travelers on the UF campus and beyond. The objectives of this study were to conduct a scan of active practice, based on interviews with national and international experts and stakeholders, and to conduct a thorough review of the related literature.

The interviews generated important insights into the landscape of AVs, highlighting both their potential benefits and the challenges that need to be addressed. This report summarizes expert opinions regarding the main benefits of AV shuttles, key challenges, promising use cases, related issues DOTs are likely to face, and information related to the latest breakthroughs on AV technology.

The literature review considered the deployment of AVs from various perspectives: technology, infrastructure, public acceptance, regulations, and alternatives to AV. It was concluded that 5G technology is crucial for ensuring smooth operation, connectivity infrastructure would significantly enhance navigation, exposure to AV results to increased willingness to use it. Finally, economic sustainability and broader adoption depend on efficient operational strategies, innovative funding models, public-private partnerships, and factors influencing mode choice.

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Executive Summary

At the state and national levels, there is continued interest in AV technologies and in providing a broad set of transportation options. For example, in Jacksonville and other cities in Florida, there are pilots and projects underway to incorporate AV shuttles into public transit. Furthermore, technologies such as mobility on demand, ridesharing, and micromobility provide alternative options. Research is needed to understand how AV shuttles and other advanced technology-based options may offer solutions to the transportation challenges faced by travelers. For example, the coupling of ridesourcing (e.g., Uber and Lyft) and autonomous driving could be a game changer that disrupts transit operations and the transportation industry. Assessing which options within this highly dynamic and rapidly evolving technological arena are best suited to meeting the varying and often complementary transportation demands and applications requires attentive awareness to the most current trends, analyses, and trials.

The objectives of this research project were to:

1. Conduct a scan of active practice based on interviews with national and international experts and stakeholders, and a thorough review of the literature. The research team contacted a diverse group of experts to solicit their opinions on personal mobility-focused AV and the use cases for public transit. We also engaged stakeholders, reviewed, and critically evaluated the development of AV technologies, their planned deployment in Florida and nationwide, their effects on existing modes and options, and their potential to provide reliable and safe public transit.
2. Assess through a thorough literature review advanced technology-based transit options such as AV shuttles, mobility on demand, ridesharing and micromobility for their advantages and disadvantages.

The research team identified and interviewed 10 experts who provided their assessment of existing and planned AV shuttle use cases, AV shuttle technology and its viability for public transit, AV costs and benefits, AV-related research, and competing modes for public transit. Experts included industry experts, university representatives, and other public and private agency representatives. The interviews generated important insights into the landscape of AVs, highlighting both their potential benefits and the challenges that need to be addressed. This

report summarizes the expert opinions recorded regarding the main benefits of AV shuttles, key challenges, promising use cases, related issues DOTs are likely to face, and information related to the latest breakthroughs on AV technology.

The literature review considered the deployment of AVs from various perspectives: technology, infrastructure, public acceptance, regulations, and alternatives to AV. It was concluded that 5G technology is crucial for ensuring smooth operation, connectivity infrastructure would significantly enhance navigation, exposure to AV results to increased willingness to use it. Finally, economic sustainability and broader adoption depend on efficient operational strategies, innovative funding models, public-private partnerships, and factors influencing mode choice.

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List of Acronyms

5G-NR	5G New Radio
ADAS	Advanced Driver Assistance System
AV	Automated Vehicle
ADS	Automated Driving System
AMoD	Autonomous Mobility on Demand
AP	Average Precision
AS	Autonomous Shuttle
ASAAS	Autonomous Shuttle as a Service
AV	Autonomous Vehicle
CAN	Controller Area Network
CL	Camera-Lidar
CLR	Camera-Lidar-Radar
CNN	Convolutional Neural Networks
CoG	City of Gainesville
CR	Camera-Radar
CV2X	Cellular Vehicle-to-Everything
DSRC	Dedicated Short-Range Communications
ECU	Electronic Control Unit
EM	Electromagnetic
eMBB	enhancing Mobile Broad Band
EV	Electric Vehicle
F&LM	First- and Last-Mile
FDOT	Florida Department of Transportation
FIFO	First In, First Out
FL	Fuzzy Logic
FMVSS	Federal Motor Vehicle Safety Standard
GNSS	Global Navigation Satellite System
IMU	Inertial Measurement Unit
IPU	Information Processing Unit
LIN	Local Interconnection Network
LOB	Lidar Occupancy Boards
LSAV	Low-Speed Autonomous Vehicle
LTE	Long-Term Evolution
mMTC	massive Machine Type Communication
MOST	Media-Oriented Systems Transport
MVF	Multi-View Fusion
NDT	Normal Distributions Transform
NHTSA	National Highway Traffic Safety Administration

NIR	Near-Infrared
NIST	National Institute for Standards and Technology
OBU	Onboard Unit
ODD	Operational Design Domain
PEOU	Perceived Ease of Use
PU	Perceived Usefulness
RIDOT	Rhode Island Department of Transportation
RL	Radar-Lidar
RNN	Recurrent Neural Networks
RSU	Roadside Unit
SAM	Shared Autonomous Mobility
SAMS	Shared Autonomous Mobility Service
SPaT	Signal Phase and Timing
TAM	Technology Acceptance Model
TPB	Theory of Planned Behavior
TRA	Theory of Reasoned Action
TSP	Transit Signal Priority
USDOT	U.S. Department of Transportation
UF	University of Florida
UFTI	University of Florida Transportation Institute
URLLC	Ultra-Reliable Low Latency Communication
UTAUT	Unified Theory of Acceptance and Use of Technology
V2I	Vehicle-to-Infrastructure
V2N	Vehicle-to-Network
V2P	Vehicle-to-Pedestrian
V2V	Vehicle-to-Vehicle
V2X	Vehicle-to-Everything
VFE	Voxel Feature Encoder
VRU	Vulnerable Road Users
VSA	Voxel Set Abstraction
VSR	Volume-to-Surface Area Ratio

1 Project Background

The University of Florida (UF) and its Transportation Institute (UFTI), the Florida Department of Transportation (FDOT) and the City of Gainesville (CoG) have partnered to create I-STREET (Implementing Solutions from Transportation Research and Evaluation of Emerging Technologies). The principal objective of the three partners in developing I-STREET was to make significant improvements to transportation safety and mobility. I-STREET is a real-world living lab with diverse technology installed and embedded in the transportation infrastructure on and surrounding the UF campus in Gainesville, Florida. It also includes an expanding set of diverse technology installed on segments of Interstate 75 in Florida.

As part of I-STREET, FDOT funded through the CoG the deployment of an autonomous vehicle (AV) shuttle, which operated in the downtown Gainesville area from February 2020-September 2022. Research conducted over the past two years showed that the speed of the shuttle was too low for the selected location (2nd Avenue). Also, due to COVID, the ridership was much lower than expected, and therefore, the research findings from that pilot are limited. However, the general population as well as older adults and people with disabilities who were surveyed before and after riding in the shuttle showed a significant increase in their intention to use the shuttle, a decrease in perceived barriers, and an increase in acceptance of this mode of transportation.

At the state and national levels, there is continued interest in AV technologies and in providing a broad set of transportation options. For example, in Jacksonville and other cities in Florida, there are pilots and projects underway to incorporate AV shuttles into public transit. Furthermore, technologies such as mobility on demand, ridesharing, and micromobility provide alternative options. Research is needed to understand how AV shuttles and other advanced technology-based options may offer solutions to the transportation challenges faced by travelers. For example, the coupling of ridesourcing (e.g., Uber and Lyft) and autonomous driving could be a game changer that disrupts transit operations and the transportation industry. Assessing which options within this highly dynamic and rapidly evolving technological arena are best suited to meeting the varying and often complementary transportation demands and applications requires attentive awareness to the most current trends, analyses, and trials.

The objectives of this research project were to:

1. Conduct a scan of active practice based on interviews with national and international experts and stakeholders, and a thorough review of the literature. The research team interviewed a diverse group of experts to solicit their opinions on what is coming regarding personal mobility-focused AV and the use cases for public transit.
2. Assess through a thorough literature review advanced technology-based transit options such as AV shuttles, mobility on demand, ridesharing and micromobility for their advantages and disadvantages.

The next section of the report summarizes our findings from interviewing experts, while the third section summarizes the literature review. The last chapter provides conclusions and recommendations from this research.

2 Discussions with Experts and Other Stakeholders

The objective of this part of the research was to identify a minimum of 10 experts and stakeholders to provide their assessment on existing and planned AV shuttle use cases, AV shuttle technology and its viability for public transit, AV costs and benefits, AV-related research, and competing modes for public transit. Experts interviewed included industry experts, university representatives, and other public and private agency representatives.

The research team developed an initial script with a series of questions to be used in the discussion. This script was reviewed by FDOT staff, and their feedback was incorporated to produce the final script used in the interviews. More than 10 individuals were identified for participation and their names were reviewed by FDOT prior to conducting interviews.

After the interviews were completed, the research team assembled the responses to provide an assessment of the potential of AV shuttles to be included in public transit, an assessment of other transit modes, and an assessment of the potential of AV technology to affect these modes.

The remainder of this chapter discusses the script used, the selection of the experts interviewed, as well as provides an overall assessment of anticipated technological developments and their timing in conjunction with their potential impacts on public transit. The chapter ends with a summary of our findings from these discussions.

2.1 Interview Script, Selection of Experts for Interviews, and Interview Process

The research team developed the following list of questions in collaboration with FDOT staff:

- In what capacity have you been involved with autonomous mobility technology?
- Based on your observation and prediction, what are the main benefits of AV shuttle mobility? Is there evidence about the safety and/or mobility benefits from AV shuttle projects? If yes, can you cite examples?
- What have you experienced as the challenges for a successful implementation of such AV shuttle projects? (legal/regulatory, technical, infrastructure, operational, maintenance, etc.)
- What are the most promising use cases for AV shuttles? How would AV shuttles affect other shared mobility options (e.g., ride hailing and shared micromobility) over time?
- Based on your observation and prediction, what are the main shortfalls of AV shuttles? E.g., not suitable for people with disabilities, mobility issues. Current vehicles are not designed for anyone except for people with good physical abilities.

- In your opinion, what are the positive and negative impacts of AV technologies and policy responses on disadvantaged groups at every stage of regulation development and infrastructure funding?
- What are the areas or issues the DOTs should be prepared to address in the near future?
- Do AV shuttles interact with transportation infrastructure such as traffic signals and/or with emerging applications/ connected and automated vehicles in real-time?
- How are AV shuttle companies addressing key issues for police and emergency response related to Avs?
- What were the latest breakthrough innovations that improved or are expected to improve the overall performance of AV Shuttles?

A list of experts was initially identified and submitted to FDOT. Once the final list was approved, the research team began scheduling and conducting the interviews. Some experts did not respond to our invitation, therefore the research team included additional experts to the list. The names of all interviewees are provided in Appendix A along with the notes of each interview.

Each interview lasted between 30 to 45 minutes. When conducting the interviews, the research team referenced this list but did not strictly follow the sequence. Sometimes we skipped questions because the interviewees had already addressed them when answering a previous question. In addition, most interviewees provided either no response or very short responses to several questions.

2.2 Synthesis of the Experts' Responses

In our interview process, we adopted a structured approach that involved asking interviewees five general questions. Additionally, we tailored our interviews by addressing the background-specific questions according to their individual backgrounds. These background-specific questions were integrated into this document as part of the general themes we explored during the interviews. The five general questions are summarized below:

- **Based on your observation and prediction, what are the main benefits of AV shuttles?**

We explored the advantages that AV shuttles offer compared to traditional transportation modes. Industry experts and professionals shared their insights on the specific benefits of AV shuttles, such as increased safety, reduced congestion, and improved accessibility.

- **What are the key challenges that AV shuttle projects face when it comes to successful implementation of AV technologies?**

We delved into the challenges faced during the implementation of AV technologies, with a particular focus on recent AV shuttle pilots in the United States. This section highlighted the technical, regulatory, infrastructure and societal hurdles that need to be overcome for widespread adoption.

- **What are the most promising use cases for AV technologies?**

We discussed the most promising use cases that leverage the transformative potential of AV shuttles. Experts provided insights into scenarios where AV shuttles can make a significant impact, such as last-mile transportation, public transit augmentation, and mobility solutions for underserved communities.

- **What are the areas or issues the DOTs should be prepared to address in the near future?**

We explored the areas that DOTs should be prepared to address in the near future regarding AV shuttle deployment. This included regulatory frameworks, infrastructure considerations, and coordination efforts to ensure the safe integration of AV shuttles into existing transportation systems.

- **What are the latest breakthrough innovations that have improved or are expected to improve the overall performance of autonomous mobility technologies?**

We examined the latest breakthrough innovations that are expected to improve the overall performance and operations of AV shuttle technologies. Experts shared insights into cutting-edge developments, such as AI-driven algorithms, and connectivity solutions, shaping the future of AV shuttles and the transportation system as a whole.

By structuring our analysis around these interview questions, we aimed to provide a comprehensive understanding of AV shuttles in comparison to other transportation modes, shedding light on both their potential benefits and the challenges that lie ahead.

2.2.1 Main Benefits of AV Shuttle Technology

In this section, we discuss the findings for the interview question:

“Based on your observation and prediction, what are the main benefits of AV shuttles?”

The advent of AVs raised discussions about the viability of integrating AVs into the existing transportation infrastructure. The experiences shared by interviewees in implementing AV-related projects serve as invaluable guides for recognizing the potential benefits and determining the profitability of operating AVs. This section discusses the advantages that the interviewees indicated would stem from the integration of AV technology into the transportation network.

2.2.1.1 Safety

In the context of transportation concerns, safety emerged as one of the most critical issues. Meghan Grela, with expertise in innovation and product strategy at Via Rideshare and a focus on fleet management, and Tim Haile, the Executive Director of Contra Costa Transportation Authority firmly, believe that AVs technology can improve traffic safety. Lucienne Pears, who holds the position of Vice President of Economic and Business Development at Babcock Ranch, shares this belief, emphasizing that safety is particularly notable in entertainment trips. She states, "There are a lot of safety benefits, specifically when you think about incorporating AVs for your entertainment travel for residents. Entertainment travel at that point in time, really happy hour, and events like that, providing an alternative option that's just as convenient. That's the biggest from a safety perspective."

Zayn Mashat, representing Ohmio, a company specializing in autonomous mobility solutions, considers incident measurement as an indicator of safety improvement, stating, "We have a 'knock on wood' 0 incidents or safety concerns. So that's already an improvement." In this vein, both Qianli Ma, an industry expert with a background in mechanical engineering and autonomous technology, and one of the interviewees, acknowledges the elimination of human errors and continuous road monitoring by AV as the cause of incident reduction. Qianli Ma said: "We are humans, not perfect. We make human errors from time to time. So having a machine that's always looking out for what's happening on the road ultimately can increase the safety level." This is achieved through the utilization of various autonomous systems, as Gordon Glass states: "The vehicles are programmed. They have so many redundant systems with regards to safety sensors, lidar (light detection and ranging), radars, sonar, etc. They've actually been able to prevent incidents from occurring."

However, gaining this benefit is challenging, and in this aspect, John Schmotzer, a professional specializing in business development for enterprise infrastructure within the automotive sector, delves deeper and refers to efficient model training as one of the most critical components. He notes, " A prerequisite for ensuring the accuracy of models in avoiding real-world collisions and events is the availability of a comprehensive dataset for training. It is crucial to have extensive data sets to train the model effectively.”

2.2.1.2 Accessibility and Mobility

One of the other important benefits that can be achieved with the advent of AV technology is providing efficient transportation for a wide range of passengers, particularly for individuals who do not own or have the ability to operate a vehicle. For example, Zayn Mashat noted: “It's actually improving the life of people who would otherwise be required to order a taxi or they are always dependent on somebody else. With the autonomous shuttle (AS), they're no longer dependent on someone else, but they can get around without having to call someone for assistance.” Both Clayton Tino (the CTO of Beep) and Gordon Glass mention the utilized technology in AVs that can help disabled people use AVs. Gordon Glass said: “Most of the vehicles that we're seeing have the ability for ramps for real users in a wheelchair. And then they're also looking at technologies for people with sight impairments or just other things where they can have different elements of verbal and different things that they can assist with.”

Tim Haile holds a broader perspective in terms of dependence: “The aim is to understand how AVs can support the growing aging community, addressing challenges such as a lack of cell phones or the need for attendants. This shared AV initiative within the senior community ensures access to groceries, goods, community centers, and social interactions, enhancing the quality of life for seniors who might otherwise rely on family and friends for transportation.”

Moreover, Lucienne Pears refers to a group of people who are over an age where they may not feel comfortable driving. AVs can enable them to access their desired destinations and address their mobility problems.

2.2.1.3 System Connectivity

AVs can also play a crucial role in establishing first-mile/last-mile connectivity. Tim Haile noted: “The main prerequisite for making micro transit work is thinking about how to provide shared AVs through the vision of a first and last mile solution. For example, providing shorter trips within two miles and facilitating connections to key locations such as downtown areas, businesses, and transit centers”. According to Gordon Glass's experience, this benefit was evident in a university on-campus project, where AV shuttles effectively transported students. Furthermore, Zayn Mashat referred to another project that utilized a specific mobile app to call over AVs. These vehicles were then scheduled to follow a route, pick people up at designated locations, and connect them to the local bus station or train station. In this context, AV shuttles can integrate with other modes of transportation, enhancing overall system efficiency.

2.2.1.4 Public Engagement of Autonomous Mobility

"Operating AVs provide a golden opportunity to explore the unknown future,” Derrick Breun, an experienced professional in AV transit projects states. He added that “AV operation allows the public to touch and feel what the future is, and it's a great way to adapt to the future of transit, which is what we need to do.” Tim Haile also commented: “Engaging with different projects enables us to understand the ways to implement these new technologies, support certain use cases, learn what its applications are, and what its abilities are.” Lucienne Pears clarified that while there is a significant hurdle of fear—fear of the new, fear of the unknown, fear of the different - there's also a high desire to adopt new technology. Gordon Glass’s statement emphasizes this point: “We've also seen a huge interest from a wide gamut of riders. So, many people will actually come and ride on one of these innovative solutions just to see what it's like, and the overall feedback is really positive.” Zayn Mashat embraces the idea that there is a lot of support and government grants for this technology, which helps it to grow slowly. “So, we just need to make sure that it continues to grow and improve,” he said.

2.2.1.5 Traffic Operation

Several interviewees noted that the AV shuttle technology can be a great aid in keeping headway consistency because of eliminating the drivers’ error. Therefore, it can have a significant impact on reducing congestion. In general, utilizing connected AVs as a concept to harmonize traffic can enhance traffic flow on highways and overall transportation efficiency, provided average headways are shorter than those of conventional vehicles.

2.2.1.6 Economic Perspectives

Clayton Tino indicates that AVs operation has the potential to pose a positive effect on the economy. The speaker emphasizes the belief that AVs have the potential to revolutionize public transit, particularly in cities like Atlanta. They argue that multi-passenger shuttles powered by autonomy technology can address two key issues: reducing the high operating costs associated with services like paratransit and enhancing traditional bus lines that often struggle with capacity issues. The speaker emphasizes that the goal is not to replace buses but to complement them, creating a more efficient and accessible public transit system that keeps people engaged and improves point-to-point mobility outcomes.

Moreover, one of the interviewees emphasized the fact that there is a high operational cost associated with traditional buses and some of them have very low ridership. In this situation, the operation of AVs can function as a more efficient alternative. AVs have the potential to reduce vehicle costs, making them more affordable compared to traditional buses. Additionally, bulk purchasing at the state level could further lower unit costs, potentially making AVs a cost-effective solution even if multiple vehicles are required to replace one bus.

From Qianli Ma's perspective, traditional rideshare services require paying human drivers' salaries and insurance. Thus, AVs would eliminate the need for human drivers and associated costs. Also, they would ensure efficient route planning, reducing detours and optimizing fuel efficiency, leading to cost reduction and improved overall transportation network efficiency. At the same time, AVs bring up serious concerns regarding bus drivers' jobs. However, one of the interviewees responds to these concerns by explaining that bus drivers can be easily converted to transit customer service representatives. They would still be there to assist disabled riders or users and handle any possible issues on the bus, without focusing on the driving side. Furthermore, from an economic development standpoint, Tim Haile supports the idea that “AV implementation will create various job opportunities.”

2.2.1.7 Summary

In summary, the experts interviewed indicate that AVs can offer a multitude of potential benefits. They have the potential to improve safety, reduce incidents, enhance accessibility and connectivity, lay a strong foundation for exploring the unknown future, have a positive impact on social feedback, eliminate human error, make traffic operations more efficient, and introduce a more cost-effective technology.

2.2.2 Main Challenges of AV Shuttle Operations

In this section, we discuss findings for the interview question:

"What are the key challenges that AV shuttle projects face when it comes to successful implementation of AV technologies?"

The interviews with professionals in the AV technology industry have shed light on several key challenges related to the implementation of AS technologies. The insights gathered collectively highlight common themes and concerns within the field.

2.2.2.1 Infrastructure Challenges

Several interviewees in the AV technology industry have underscored the significant challenges associated with infrastructure readiness in the United States. Clayton Tino and Derrick Breun have both emphasized the crucial issue of connectivity. Tino highlighted the varying quality of roadways and inconsistent 3G or 4G coverage across different regions, which poses difficulties in delivering reliable autonomous services. Similarly, Breun identified robust communication between Onboard Units (OBUs) and traffic signal elements as a key challenge, particularly concerning connectivity. The challenges related to left-hand turns, whether unprotected or protected, are, also, expected to persist in autonomous driving. Clayton Tino reported that one approach to address this challenge involves implementing multiple layers of safety checks. This includes having a perception system that can interpret traffic signals and using Vehicle-to-Infrastructure communication (V2I) to validate the signal's phase, thus ensuring the accuracy of intersection status.

In addition to these connectivity challenges, interviewees have also voiced concerns about modifying prescribed routes in response to construction or road modifications. Derrick Breun pointed out the complexities of altering these routes, involving remapping and approvals, which can be time-consuming and impact the vehicle's operations. Tim Haile highlighted the necessity of digitized infrastructure and emphasized that by digitizing elements like work zones and road activities, cities can enable AVs to make safer route choices, thus addressing critical infrastructure challenges.

Zayn Mashat stressed there is an urgent need for substantial improvements in charging infrastructure. Mashat also noted that project delays often result from unresolved charging solutions.

On the other hand, Lucienne Pears offered a different perspective. She underscored that the primary challenge lies not in the infrastructure itself but rather in securing the necessary funding to establish a pilot program and conduct a comprehensive study of its long-term viability. She believed that these infrastructure challenges can be largely solved if considerations of autonomous mobility technology are incorporated into the planning and development of the transportation system when new communities are built.

2.2.3 Regulatory Challenges

Regulatory challenges emerge as another prominent obstacle according to multiple interviewees. Clayton Tino emphasized the deficiency of clear, standardized regulations and minimum performance requirements for AVs on U.S. public roads, contrasting it with Europe's well-established regulatory framework. The absence of such standards in the United States generates uncertainty and potential impediments to the widespread deployment of ASs. Tim Haile further underscored this concern by emphasizing the necessity for federal regulatory clarity, a prerequisite for promoting safety and enabling the broader implementation of autonomous technologies. Specifically, he called for the development of federal safety standards tailored to purpose-built AVs. He explained that the current absence of these standards, particularly for vehicles that lack traditional controls like steering wheels, brake pedals, and gas pedals, contributes to uncertainty among manufacturers and hampers the advancement of purpose-built AVs.

From a geopolitical standpoint, considerations encompass safety, security, and privacy when collecting telemetry and vision-based data. John Schmotzer states that obtaining customer consent and complying with regulations like General Data Protection Regulation (GDPR) in Europe add further complexity.

These shared perspectives highlight the pressing need for regulatory harmonization, standardized safety protocols, and an environment favorable to innovation in the AV sector.

2.2.4 Technological Challenges

Qianli Ma emphasized the complexity of developing planning, perception, and prediction algorithms. These are the core technologies behind AVs, but they involve addressing unsolved problems. Unlike established industries with clear requirements and processes, self-driving cars lack defined standards for their features and behaviors. The challenge lies in validating and ensuring the safety of these technologies, especially when dealing with edge cases and unpredictable scenarios. The need for extensive data collection and continuous training of autonomous systems adds complexity to deployment.

Dr. Razul Razdan, who brings extensive experience in CPU design and semiconductor development, emphasized the presence of fundamental technological barriers that must be surmounted before AVs can achieve widespread acceptance. These obstacles encompass the critical need for verifying AI components, particularly within safety-critical systems.

Finally, John Schmotzer highlighted a crucial concern regarding the cost of precise data collection in the AV industry. He pointed out the substantial variability in data collection expenses, spanning from as high as $50 per mile to as low as 2 cents per mile. These expenses encompass the entire process of acquiring and labelling data essential for training AV systems.

2.2.4.1 Lack of Funding

In response to Derrick Breun's comment, it's evident that funding large-scale projects related to AVs has encountered its fair share of challenges. Initially, there was a surge of interest and numerous proposals in the field. However, this momentum seems to have waned in recent times, with AVs no longer dominating the transit discourse as they once did. Consequently, available funding for these ambitious projects has decreased, posing a hurdle for their realization.

Another significant challenge lies in the manufacturing sector, where the landscape has transformed. The market for AV technology has witnessed financial consolidation, resulting in fewer manufacturers both in the United States and abroad. This reduced pool of technology providers creates a more competitive environment and limits the options available for sourcing AV units, further complicating the funding and implementation of large-scale projects in this rapidly evolving field.

2.2.4.2 Summary

In summary, the AV industry faces a multitude of challenges across various fronts. Infrastructure challenges, such as connectivity issues, modifying routes, and insufficient charging infrastructure, impede the seamless deployment of AVs. Regulatory hurdles stemming from the absence of standardized regulations, especially in the United States, create uncertainty and hinder progress. Technological complexities in developing planning, perception, and prediction algorithms, as well as verifying AI components, are substantial barriers. Additionally, the cost of precise data collection varies significantly and poses economic challenges. Poor planning, navigating mixed traffic, and industry competition further complicate the successful implementation of AV projects. Finally, funding for large-scale AV projects has declined due to waning interest and reduced funding availability, while a consolidated manufacturing sector has limited technology options, posing challenges for project realization. Addressing these multifaceted challenges, from infrastructure and regulation to technology and insufficient planning, is vital for realizing the widespread adoption of AVs.

2.2.5 Promising Use Cases

In this section, we discuss findings for the interview question:

"What are the most promising use cases for AV technologies?"

Exploring the most promising use cases of AV technologies provides insights and perspectives from industry experts that contribute to our understanding of the potential of AVs in various transportation scenarios.

2.2.5.1 Confined Environments

Overall, interviewees collectively recognize the value of AV in confined or controlled environments. Derrick Breun highlights the promise of public ASs, particularly in university settings, where predictable routes can significantly enhance speed and user acceptance. He, specifically, noted that "youthful passengers tend to be very, very interested in technology. And it's a great way to adapt to the future of transit, which is what we need to do." Another use case stressed by the interviewees is the potential of AV shuttles to serve senior population and individuals with specific disabilities. Tim Haile mentions a couple of successful projects. The first initiative focuses on enhancing senior community transportation, where AVs are deployed to provide senior citizens with improved access to vital services and community hubs. This initiative addresses the common challenge faced by seniors who often rely on family or friends for transportation, offering them a newfound sense of independence and access to groceries, social activities, and community engagement. The second project, in collaboration with a county hospital, aims to tackle the issue of medical appointment cancelations, primarily caused by transportation barriers. Finally, Zayn Mashat suggests that AV shuttle services can find another valuable application in confined environments. Specifically, they can serve to enhance accessibility and convenience in areas where traditional transportation options may be limited. This includes scenarios like shuttling passengers from parking lots to airport terminals, improving the overall travel experience.

2.2.5.2 Sustainable Transportation Systems

Meghan Grela highlights the impact of AV technology in making transportation more sustainable. She mentions that rideshare and micro-transit models are particularly well-suited to address pressing challenges in transportation. These models can either replace or enhance existing transit options, which may suffer from inefficiencies.

The interaction between ASs and complementary mobility solutions such as scooters, e-bikes, and other forms of micro-mobility plays a crucial role in shaping the future of transportation and the creation of a comprehensive transportation ecosystem. Specifically, some interviewees mention that complementary mobility solutions, like scooters and e-bikes, can fill the crucial first- mile and last-mile connectivity gaps that are often challenging to address with traditional public transit systems. This integration not only enhances the overall accessibility of AV shuttles but also provides a holistic solution for commuters, reducing reliance on personal cars and reducing traffic congestion. However, as Lucienne Pears pointed out, the introduction of new mobility initiatives, including point-to-point electric ride-hailing services alongside AV shuttles, requires careful planning and coordination. Ensuring that these services complement each other rather than duplicate efforts is essential for the success of the entire transportation ecosystem.

Building upon the theme of creating a comprehensive and efficient transportation ecosystem, it's essential, also, to consider how multi-passenger AV shuttles can integrate with and enhance traditional public transit. Clayton Tino notes the challenges faced by traditional bus services, such as limited capacity and accessibility issues, which can hinder their effectiveness in providing point-to-point mobility solutions. He believes that multi-passenger AV shuttles can play a pivotal role in addressing these challenges.

Unlike specialized point-to-point services or traditional bus lines, multi-passenger AV shuttles can offer a cost-effective and flexible alternative. By leveraging autonomous technology, they can reduce operating costs while providing greater accessibility and convenience for riders.

2.2.5.3 Robo- Taxis vs Public Autonomous Transit

Despite recent challenges and suspensions affecting robotaxi companies such as Cruise, Quianli Ma believes that robotaxis remain a crucial part of the transportation future. Notably, he states that in countries with high population density, such as some Asian nations, public autonomous transit may better serve the needs of the population. However, in the United States, the robotaxi model is seen as a more promising and efficient service model compared to traditional public transit. Nonetheless, the interviewee acknowledges the importance of pushing the boundaries of autonomous driving technology to improve public services, even though certain service models may be more suitable in specific regions.

John Schmotzer sheds light on the reasoning behind capital investments and market competitions in the autonomous transportation industry. Schmotzer explains that the high costs associated with Level 5 autonomous solutions (particularly the expensive sensor stack), together with the research and development costs, result in a longer time to break even for venture capital. This, combined with the limited market potential of small shuttles, such as those operating on a college campus, makes the development of AV shuttles oriented toward public transit a low priority for major AV technology developers such as Waymo, Cruiser, and Tesla. In this context, the interviewee questions whether allocating substantial resources to low-speed AS services is as economically viable and socially beneficial as, for instance, investing in driver safety measures. His comments shed light into why major tech players such as Waymo and Tesla may have not entered the market of offering low-speed AS services. It demonstrates that the choice of service models is intricately linked to technology requirements and return-of-investment considerations.

2.2.5.4 Enhancing Transportation for the Elderly and Underserved Communities

Tim Haile's comments highlight the potential of shared AVs to address transportation challenges, particularly in underserved communities. He describes the positive feedback received from community engagement efforts, where residents expressed enthusiasm for the technology. These ASs are seen as a means to connect people to essential destinations, such as transit stations, grocery stores, downtown areas, and movie theaters. Tim underscores the convenience and accessibility of point-to-point shuttle services, which eliminate the complexities associated with navigating traditional bus transit stops. He also emphasizes the importance of serving disadvantaged communities and individuals without access to personal vehicles, believing that autonomous mobility will significantly impact accessibility. The elderly population welcomes the newfound independence and freedom offered by ASs, especially in regions with a growing senior citizen demographic. While safety concerns exist, Tim Haile noted that most respondents are excited about the future of autonomous mobility, suggesting that familiarity will increase, and positive experiences will alleviate these concerns over time.

2.2.5.5 Summary

The potential of current AV technologies encompasses use cases in confined settings, and those aiming to implement sustainable and inclusive transportation systems. Potential use cases mentioned by the experts interviewed include those aiming to improve the lives of disadvantaged communities, enhancing last-mile connectivity, or redefining urban mobility. However, these use cases are confined by the level of autonomous driving technology possessed by the AV shuttle manufacturers and operators. Major tech players such as Wayne and Telsa that offer more superior autonomous driving technology than existing AV shuttle operators have focused on the robotaxi and personal vehicle market and not the transit market. The dynamic interplay between technological advancement, market needs, and return-of-investment considerations shapes the near-term and long-term trajectory of AV shuttle development and deployment.

2.2.6 DOT Preparedness for AV Shuttle Implementation

In this section, we discuss findings for the interview question*:*

"What are the areas or issues the DOTs should be prepared to address in the near future?"

AV implementation comes with challenges and various considerations. This section provides an overview of issues DOTs may encounter in future projects.

2.2.6.1 Infrastructure

From an infrastructure perspective, John Schmotzer stated that "the investment in urban or rural-based camera vision, connected vehicle hubs, and identifying cost-efficient ways to do so, will be beneficial."

Gordon Glass raised the issue that the ODDs for AVs should be cleared by DOTs. In this regard, he asked "Are DOTs looking to operate AVs in mixed traffic or on dedicated routes? How are AVs going to load their passengers? Are they going to have station stops? Are they looking to connect AVs to signals or not?" He indicated that these questions should be answered by DOTs.

One of the interviewees indicated that he believes one of the most important areas that should be examined is roadway design change considering the AVs presence. There are some challenges in this regard including "the consistency of road marking, infrequent road updates, when and how to make necessary changes for autonomous technology, and concerns about specific markings causing conflicts, such as ultra-reflective stopovers affecting sensors". He highlighted the potential of optimizing traffic signal operations for AVs movement. However, he also acknowledges the complexity and long-term nature of transitioning to such systems.

Dr. Rahul Razdan mentioned that if DOTs want to participate in infrastructure development, there would be some potential roles such as enabling charging infrastructure and supporting sensory-based systems. In the case of sensors, there would be an essential need to occasionally calibrate, because even a minor impact can throw them out of alignment. Since the operation depends on these sensors, the question is, should you have DOT support for sensor calibration?

2.2.6.2 Regulatory Terrain

Regarding regulations, John Schmotzer commented: “Although GDPR is a wonderful thing for personal privacy, it makes AI-driven development in Europe and specifically in the US challenging, regarding aggregate data collection in a way that neither violates the intent nor the letter of the law for GDPR”. He shared his personal thoughts by saying “In my life in the automotive world, liability, security, and customer sentiment were critical metrics, and there was a lot of angst around whether we would get sued for doing something. So, being able to alleviate some of those concerns is helpful.”

Also, in terms of regulations DOTs should come up with some codes and education for emergency responders. Gordon Glass noted the different requirements of AVs: “Most of these vehicles are electric, which have different requirements. For instance, if there was a fire or something, how should emergency agencies respond to that in the vehicle?”

Tim Haile emphasized the need to digitize infrastructure and change the regulatory environment. He asserts that “the federal regulations haven't changed much, and state governments have basically created their own legislation to enable a lot of the permitting of AVs, which creates a patchwork of regulatory rights. It's essential for the federal government to step up and provide safety measures to truly enable these technologies”. Also, he said, “The other thing that we need is a federal regulatory environment around purpose-built vehicles. Right now, there are no federal motor vehicle safety standards for a vehicle that lacks a steering wheel, brake pedal, or gas pedal. This lack of standards is hindering scalability. That's why many people are still using vehicles with steering wheels and brake pedals, because that's what the current regulatory framework supports.” He added: “another significant aspect of the regulatory environment is to determine whether self-certification is appropriate or if we need a third-party validator. This is another crucial element that needs to be addressed in the federal framework in the near term.” Also, he commented that “from a federal regulatory side, the biggest challenge we have is federal funding can only be spent on components that are either made or built in the United States.”

Zayn Mashat mentioned expanding the ecosystem to make a more competitive environment. In this vein, he asserts that, “allowing new players in and being more open to innovation are the key aspects. There is a notable requirement for both more projects and increased adoption of these projects to begin with. The second part involves expanding the ecosystem, or at least partnering with entities like us to contribute to its development, rather than merely relying on the same solution repeatedly. Sticking to a small ecosystem hinders service improvement, this is why there is a requirement for a bit more competition.”

2.2.6.3 Funding

Lucienne Pears mentions that “the experiences in the AV world has shown that FDOT has done a great job of making Florida welcome and hospitable to that new technology.” She also indicated: “I understand and agree with many of the limitations on the expenditure of DOT funds, especially concerning government agencies and similar entities. However, I believe it would be really helpful if the DOT could explore different use cases, such as the university use case, the rural town use case, and the socio-economically challenged downtown use case.” Also, she suggested “If we were to look at our master plan communities at the forefront, keeping mobility and connectivity in mind, and figuring out how to drive the implementation of alternative travel resources within these new neighborhoods, I think that would be a very productive approach and would position the state well for the future. So, the challenge is not the infrastructure; it's securing the funding to launch a pilot study to assess how this could be funded long term in a specific area. we need to determine if this type of service makes sense in every area.”

2.2.6.4 Community Preparedness

Clayton Tino mentioned, “community preparedness stands as one of the crucial aspects. People have varying relationships with cars, different mobility expectations, and differing views on private versus public mobility services. To achieve success, public agencies must invest time in cultivating an environment that is ready for autonomy.”

John Schmotzer shared his thoughts on the importance of education for the population regarding this new technology by comparing the implementation speed in the United States and China. He explained, “there's currently more comfort with technology-forward decision making at both the government and cultural levels in China. The technical talent there is simply amazing. However, there's a cultural component where the DOT needs to adopt a more aggressive approach rather than just taking a backseat and receiving ideas. They should be more hands-on. China is experiencing robust government support for its automotive industry to advance technology, showcasing a proactive stance”.

2.2.6.5 Summary

In summary, the experts interviewed indicate that implementation of AVs presents several challenges across infrastructure, regulation, funding, and community preparedness. Several experts suggested that DOT must proactively address these challenges in future projects. Key considerations include optimizing infrastructure through cost-effective investments and addressing questions about AV operations on roads. Regulatory hurdles include the impact of data privacy laws (such as GDPR), liability concerns, and the need for standardized regulations for AVs and emergency response. Funding challenges may not be solely related to availability of funds. The experts indicated that despite fund availability, it is essential to explore diverse use cases and pilot programs. They also indicated that community engagement is critical considering varying expectations and relationships with AVs.

2.2.7 Latest Breakthrough Innovations for Autonomous Mobility Technologies

In this section, we discuss findings for the interview question:

“What are the latest breakthrough innovations that have improved or are expected to improve the overall performance of autonomous mobility technologies?”

The interviewees highlight several recent breakthrough innovations that have significantly improved the operation of AV technologies. John Schmotzer pointed out the emergence of generative AI and large language models for end-to-end AV models that predict future images the vehicle will encounter, paving the way for advanced decision-making. He also mentioned the experimentation with multimodal transformer models to create comprehensive world models for sensor fusion and control. Quianli Ma emphasized the advancements in machine learning and deep learning, particularly in perception and prediction, which have transitioned the industry from rule-based algorithms to data-driven approaches, increasing AV operational speed and the overall performance. He explained that deep learning techniques, such as convolutional neural networks (CNNs) and recurrent neural networks (RNNs), have enabled AVs to perceive and anticipate their surroundings more effectively. Tim Haile also underscored the potential of artificial intelligence to handle edge cases and improve AVs' adaptability to unforeseen scenarios.

Another breakthrough technological advancement in the AV industry lies in the connectivity of AVs with each other. Zayn Mashat highlighted platooning technologies, which digitally connect multiple shuttles, enabling them to operate in close coordination. He explained that this innovation offers flexible and efficient solutions for transporting varying passenger volumes, making it possible to adapt to the specific needs of different scenarios.

Gordon Glass highlighted the move from purpose-built shuttles to retrofitting existing vehicles for higher speeds and mixed traffic, providing greater capacity and route flexibility. In his perspective, these innovations collectively contribute to the continued enhancement of AV technologies, making them more capable and adaptable to various scenarios. John Schmotzer strongly opposed the idea of retrofitting traditional vehicles with self-driving kits, particularly when it involves modifying critical vehicle systems. He noted that these technologies raise concerns about the potential dangers, both from a technical and ethical standpoint associated with such practices. He, specifically, explains that modifying the Controller Area Network (CAN) to enhance a vehicle’s autonomy can harm the normal functioning of its Electronic Control Unit (ECU) which is responsible for many safety-critical functions. Quianli Ma shares similar insights with John Schmotzer and states that retrofitting kits may have been a starting point for autonomous technology but may not be the primary approach in the future.

In conclusion, recent breakthroughs in AV technologies have been transformative. Innovations such as generative AI, large language models, and multimodal transformer models have improved AV prediction and adaptation capabilities significantly. Deep learning techniques have enhanced AV perception and prediction, leading to improvements in operational speeds and overall AV performance. Digital connectivity among AVs, such as platooning technologies, offers flexibility, and retrofitting traditional vehicles for higher speeds and mixed traffic can affect AV deployment. However, the ethical and technical concerns around retrofitting kits require careful consideration. Modifying the CAN to improve a vehicle's autonomy has the potential to disrupt the regular operations of its ECU, which plays a crucial role in many safety-critical functions.

2.3 Summary and Conclusions

The interviews generated important insights into the landscape of AVs, highlighting both their potential benefits and the challenges that need to be addressed. The discussions shed light on promising use cases and breakthrough innovations, and provided recommendations for DOTs in identifying issues related to AVs that they should prepare for in the future. The main points derived from interviews are summarized below:

Main benefits of AV shuttles

- Traffic safety enhancement due to eliminating human errors.
- Accessibility and mobility advancement especially for individuals who depend on others for driving.
- Establishing first-mile/last-mile connectivity by integrating with other modes of transportation.
- Eliminating human drivers and their associated costs, optimizing fuel efficiency, and reducing vehicle expenses can contribute to providing transportation at a lower cost.
- Enhance traffic operations and potentially reduce congestion by maintaining a consistent headway that is lower than the average headway of conventional vehicles.

Key challenges of AV shuttle project implementation

- Challenges related to left-hand turns, whether unprotected or protected, are expected to persist.
- Varying road quality and inconsistent 3G/4G coverage.
- The necessity of digitized infrastructure, enabling safer route choices for AVs.
- The urgent need for substantial improvements in charging infrastructure. Unresolved charging solutions can lead to project delays.
- Need to secure the funding necessary to initiate a pilot program and conduct a comprehensive study to assess the long-term viability of a particular project or initiative.
- Lack of clear, standardized federal regulations and minimum performance requirements for AVs on U.S. public roads, which creates uncertainty and potential obstacles to the widespread deployment of ASs.
- Privacy concerns in collecting telemetry and vision-based data.

- Complexity of developing planning, perception, and prediction algorithms, which are the core of AV technologies.
- Need for verifying AI components within safety-critical systems.
- Requirement for extensive data collection and continuous training of systems, which is associated with a crucial concern about the cost of precise data collection in the AV industry.
- Intense industry competition poses challenges in marketing AS services, where overpromising and under delivering may lead to issues with public transit including low ridership and difficulties in integration into existing transit systems.

Promising use cases of AV shuttles

- CAV shuttle services can enhance accessibility in confined environments, especially for senior populations and individuals with disabilities.
- Integration of various mobility solutions such as AV mobility technologies, scooters, and e-bikes reduces reliance on personal cars, alleviating traffic congestion.
- Technology advancements on autonomous driving in the robotaxi market is more advanced than in the low-speed AV shuttle market. However, the high costs associated with developing Level 5 autonomous solutions and the relatively low market potential of low-speed AV services suggest that major tech players such as Waymo, Cruiser, and Telsa will not enter the low-speed AV shuttle market in the near future.
- Shared AVs can be utilized in serving disadvantaged communities which would lead to improving accessibility. This may be achieved by providing convenient point-to-point shuttle services that connect residents to essential destinations.

Issues that DOTs should be prepared for

- Changes in roadway design and road marking to ensure consistency.
- Define the ODDs for AVs.
- Invest in urban or rural-based camera vision, support sensor-based systems, and charging stations.
- Implement connected vehicle hubs and AV station stops.
- Perform occasional sensor calibration.
- Connect AVs to signals and potentially optimize traffic signal operations for AVs.
- Consider dedicated lanes as an alternative to solving AV operation challenges in mixed traffic.
- Develop special codes and educational programs for emergency agencies to effectively respond to AV-related events.
- Advocate for changes in the regulatory environment, emphasizing the importance of federal regulations to ensure safety measures and scalability.
- Work towards alleviating some restrictions related to GDPR.

- Advocate for exploring master plan communities and prioritizing mobility and connectivity to implement alternative travel resources.

Latest breakthrough innovations of AV technologies

- Utilizing AV technologies, including generative AI and deep learning techniques, have significantly improved prediction and perception capabilities.
- Artificial intelligence can potentially be used to handle edge cases and improve AV adaptability to unforeseen scenarios.
- Connectivity of AVs through platooning technologies may facilitate coordinated operation for efficient transportation.
- Digital connectivity may contribute to advancing AV deployment.

In addition to the items discussed in detail, the research team concluded the following based on the overall interview responses:

- Almost all interviewees believe that designing and operating AV shuttles that can serve people with disabilities is not a challenge. In fact, many AV shuttles have already incorporated accessibility considerations into their design, and almost all of them can be easily revamped to become ADA-compliant vehicles.
- Many recent AV shuttle models can communicate with traffic signals and other CAVs. The key technical challenges are the availability of the 5G network, and cybersecurity concerns.
- AV shuttle operators often engage with local public agencies and police departments to address key issues for police and emergency responses related to AV shuttles. While public safety and emergency response have not been an issue, training materials should be developed to facilitate this purpose if AV shuttles are widely deployed.

Finally, our interview work also suggests that there are many questions that have yet to be answered. Derrick Breun asks: “How are AVs going to react? How is the public going to react to the AVs? How are other vehicles going to react to the AVs? Or, how is the lidar going to work in different situations? Investigating the answers to these questions is a primary aspect of learning. That's the key reason why we do it, and want to keep doing it. It is the future of transit, and we just need to keep working on the technology, continue to innovate.”

3 Review of Published Literature on AV Shuttle Deployments

This chapter provides the results of a comprehensive literature review regarding the deployment of AV from different perspectives. This review aimed to understand the nature of AV deployment, offering a detailed discussion of the factors influencing its performance, potential challenges in deployment, and integration into existing transportation systems.
The chapter discusses the potential challenges, advantages, disadvantages, and requirements for the implementation of AVs, based on 1) case studies of AV pilot projects; 2) a technological perspective; 3) an infrastructure perspective; 4) public acceptance considerations; and 5) an overview of relevant regulations. It then provides an overview of the current challenges and opportunities within public transit systems, focusing on the integration of AVs with other transportation modes, mobility on demand, and micromobility solutions. The last section offers a summary and conclusions from the literature review.

3.1 AV Pilots and Deployments

This section provides an overview of significant AV pilots and deployments around the world. Figure 3-1 provides a map with the locations of pilots and long-term deployments of AV shuttles in Florida. The names of these pilots are listed in Table 3-1. Figure 3-2 and Table 3-2 provide the same information for deployments in the United States, while Figure 3-3 and Table 3-3 provide this information for deployments in Europe. While we aimed to include all AV shuttle projects, some were omitted if they were not publicized in the literature.

Next, we discuss a representative set of these pilot projects. In our review we selected pilots that have published comprehensive performance evaluation reports, enabling us to capture their most important characteristics and relevant findings regarding their operation. We discuss the general characteristics of these pilots (time period, use case, location), followed by ridership, operating environment and technical characteristics (operating speed, performance of automation and disengagements). Then, we evaluate the deployment of each pilot project in detail, highlighting both the potential benefits and the challenges associated with integrating AV technology into existing transportation networks.

Figure 3-1. Deployment of ASs and pilots across Florida

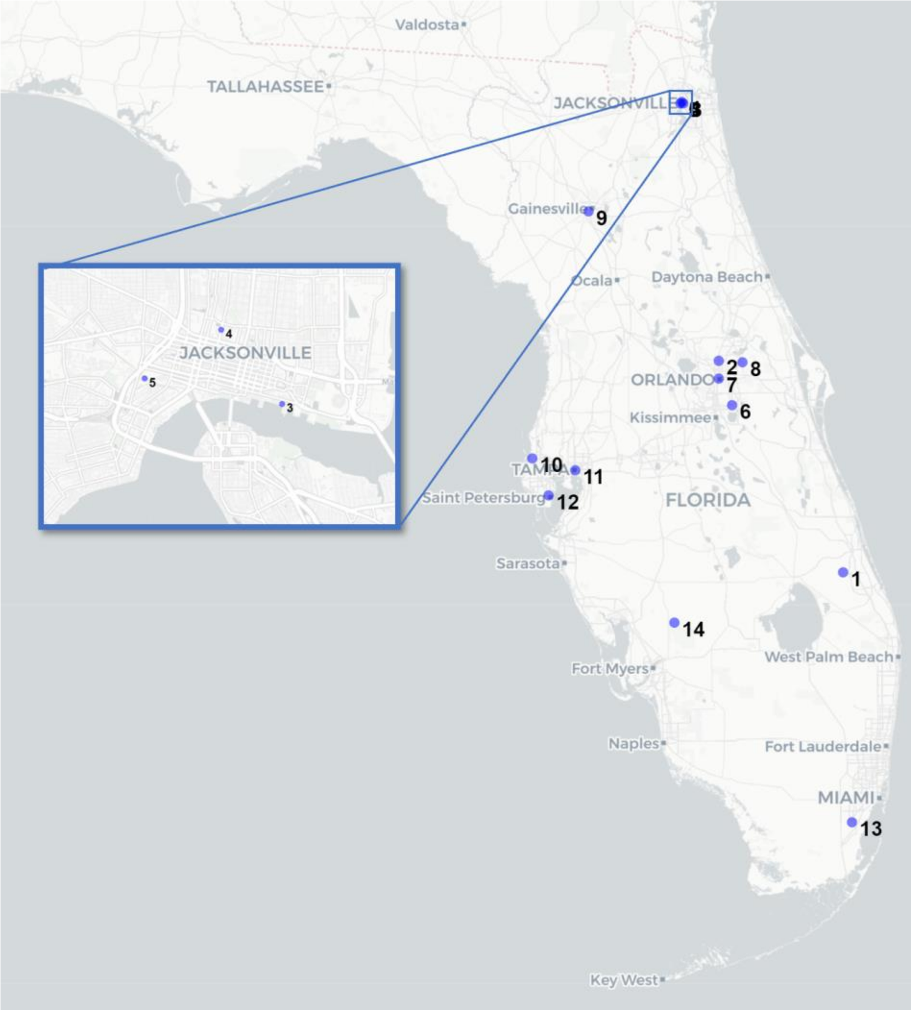


Table 3-1. Locations of the ASs and pilots across Florida

	Program Name	**City**
1	Tradition in Motion	Port St. Lucie
2	CraneRIDES	Altamonte Springs
3	U2C: Bay Street Innovation Corridor	Jacksonville
4	U2C: FSCJ Campus	Jacksonville
5	U2C: Skyway Conversion	Jacksonville
6	Move Nona	Lake Nona
7	SWAN AV Shuttle	Orlando
8	ATTAIN Central Florida	Orlando
9	Gainesville Autonomous Transit Shuttle	Gainesville
10	Pinellas Suncoast Transit Authority	Tampa
11	HART SMART AV Program	Tampa
12	PSTA AVA	Tampa
13	Miami-Dade DTPIW's AV Shuttle Pilot	Miami
14	Babcock AV Shuttle	Babcock Ranch

Figure 3-2. Deployment of ASs and pilots across the United States

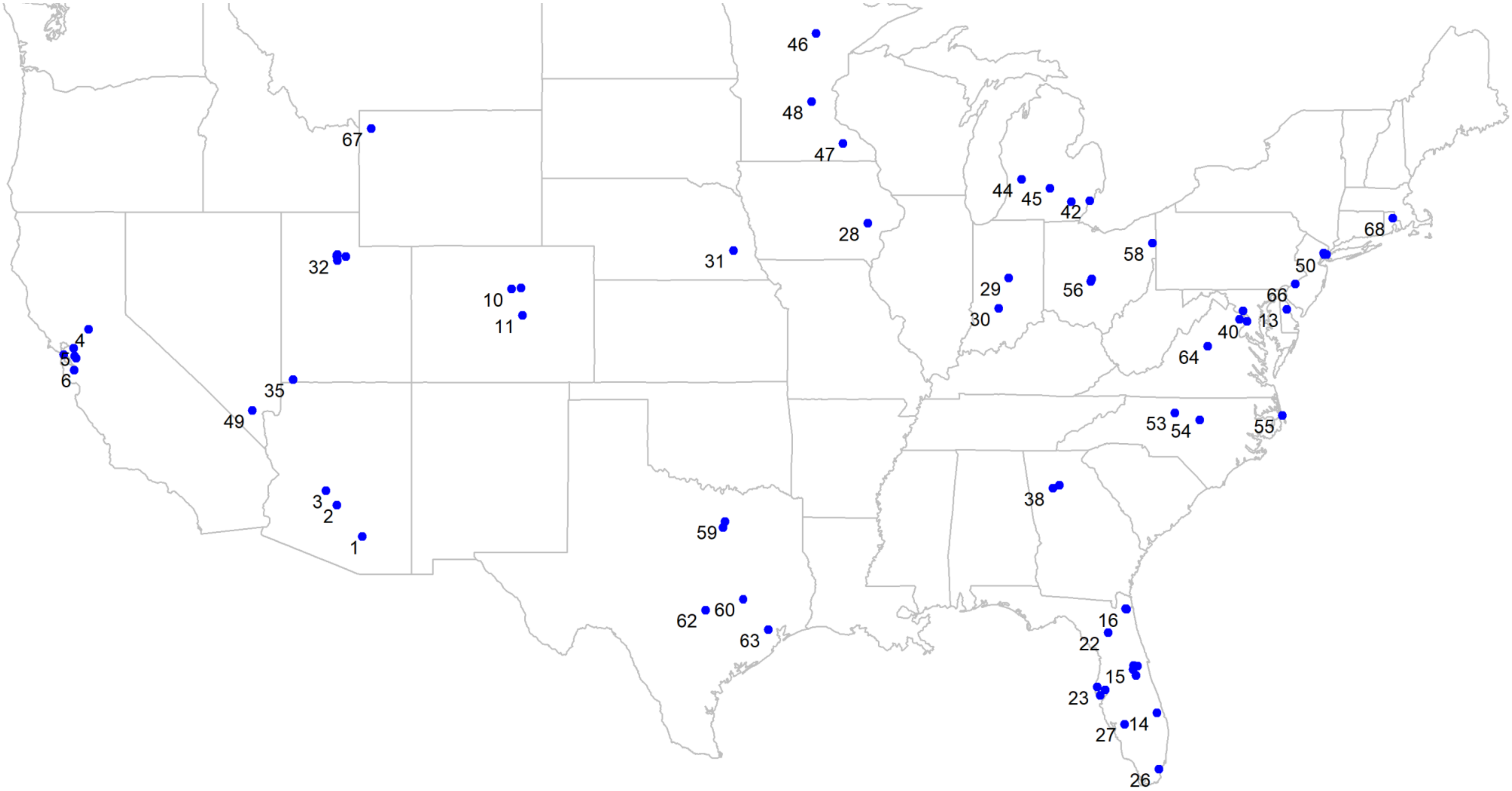


Table 3-2. Locations of ASs and pilots across the United States

	Program Name	**City**	**State**
1	Valley wAVe	Sun City	Arizona
2	RideChoice Waymo	Phoenix	Arizona
3	Robo Ride	Peoria	Arizona
4	Rancho Cordova Olli Shuttle Program	Rancho Cordova	California
5	Gomentum Station	Concord	California
6	Accessible Automated Vehicle Project	Santa Clara	California
7	SAV	Dublin	California
8	Treasure Island	San Francisco	California
9	Bishop Ranch	Contra Costa	California
10	AvCo	Golden	Colorado
11	Fort Carson	Colorado Springs	Colorado
12	61AV	Denver	Colorado
13	DelDOT AV Shuttles	Dover	Delaware
14	Tradition in Motion	Port St. Lucie	Florida
15	CraneRIDES	Altamonte Springs	Florida
16	U2C: Bay Street Innovation Corridor	Jacksonville	Florida
17	U2C : FSCJ Campus	Jacksonville	Florida
18	U2C: Skyway Conversion	Jacksonville	Florida
19	Move Nona	Lake Nona	Florida
20	SWAN AV Shuttle	Orlando	Florida
21	ATTAIN Central Florida	Orlando	Florida
22	Gainesville Autonomous Transit Shuttle	Gainesville	Florida
23	Pinellas Suncoast Transit Authority	Tampa	Florida
24	HART SMART AV Program	Tampa	Florida
25	PSTA AVA	Tampa	Florida
26	Miami-Dade DTPIW's AV Shuttle Pilot	Miami	Florida
27	Babcock AV Shuttle	Babcock ranch	Florida
28	ADS for Rural America	Iowa City	Iowa
29	Together in Motion	Fishers	Indiana
30	Fast Forward Bloomington	Bloomington	Indiana
31	Navya Autonomous Shuttle	Lincoln	Nebraska
32	Automated Shuttle Pilot	Farmington	Utah
33	Automated Shuttle Pilot	Salt Lake City	Utah
34	University of Utah Autonomous Shuttle	Salt Lake City	Utah

Table 3-2, continued

	Program Name	City	State
35	Automated Shuttle Pilot	St. George	Utah
36	Automated Shuttle Pilot	Sandy	Utah
37	Automated Shuttle Pilot	Park City	Utah
38	The Cumberland Hopper	Atlanta	Georgia
39	PAUL	Peachtree Corners	Georgia
40	Olli	National Harbor	Maryland
41	Olli	Montgomery County	Maryland
42	Detroit Hospital Autonomous Shuttle	Detroit	Michigan
43	A2GO	Ann Arbor	Michigan
44	AVGR	Grand Rapids	Michigan
45	MSU Automated Bus	Lansing	Michigan
46	goMARTI	Grand Rapid	Minnesota
47	Med City Mover	Rochester	Minnesota
48	MnDOT Autonomous Bus Pilot Project	Minneapolis	Minnesota
49	AAA Free Self DrivingShuttle	Las Vegas	Nevada
50	Optimus Ride	New York	New York
51	Ohmio (John F. Kennedy Int.Airport)	New York	New York
52	Coast Autonomous P-1 Shuttle	New York	New York
53	Aggie Auto	Greensboro	North Carolina
54	CASSI (Cary's Bond Park)	Cary	North Carolina
55	CASSI	Kill Devil Hills	North Carolina
56	Linden LEAP	Columbus	Ohio
57	Smart Circuit	Columbus	Ohio
58	Smart2 Network	Youngstown	Ohio
59	DFW EasyMile	Dallas	Texas
60	Texas A&M	College Station	Texas
61	RAPID	Arlington	Texas
62	RATP Dev	Austin	Texas
63	TSU AV Shuttle (Texas Southern University)	Houston	Texas
64	AVNU	Commonwealth	Virginia
65	Relay Shuttle	Merrifield	Virginia
66	Pennsylvania's first AV shuttle	Philadelphia	Pennsylvania
67	T.E.D.D.Y.	Canyon Village	Wyoming
68	Little Roady	Providence	Rhode Island

Figure 3-3. Deployment of ASs and pilots across Europe

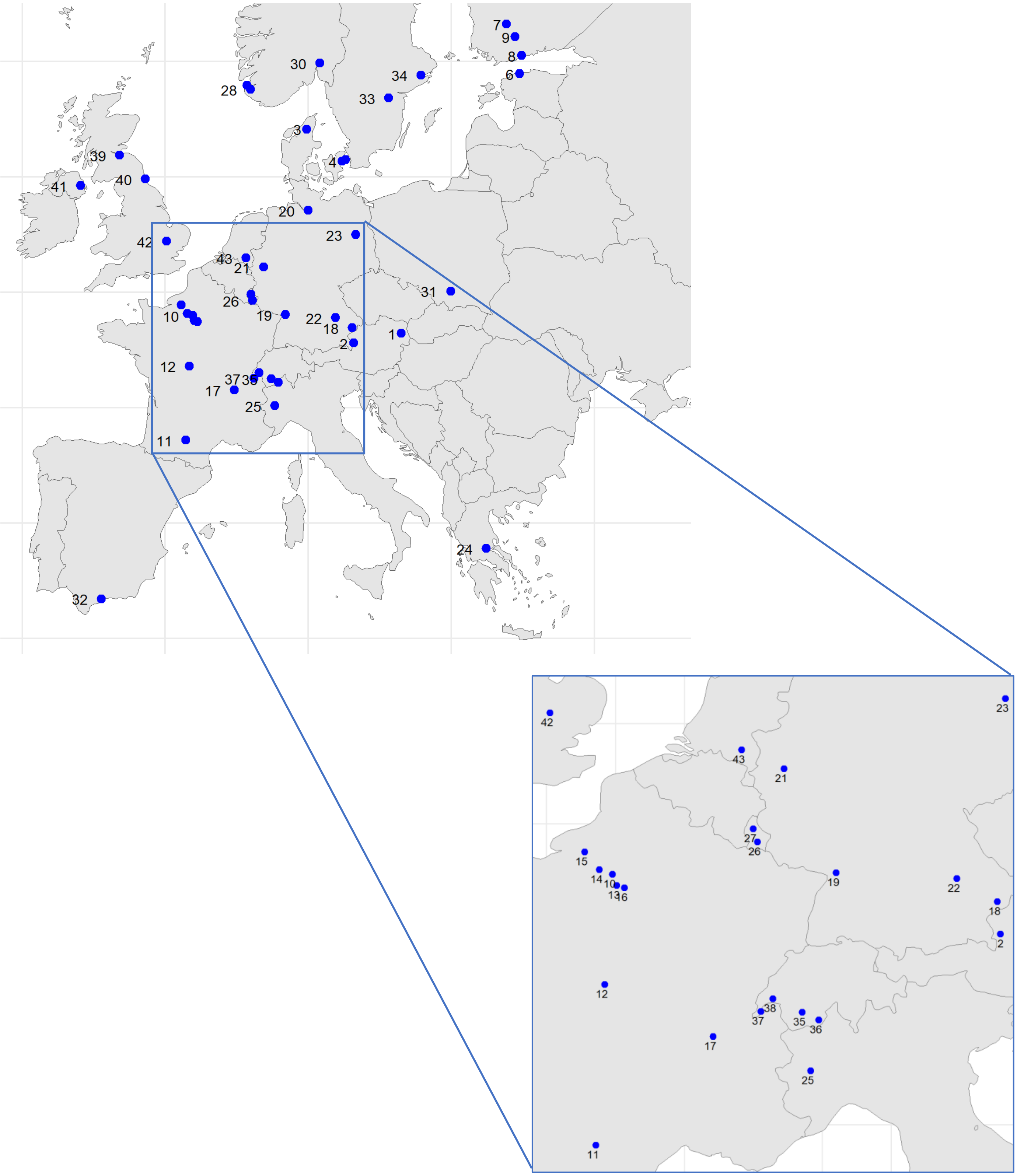


Table 3-3. Locations of ASs and pilots across Europe

	Program Name	**City**	**Country**
1	GreenHopper	Aalborg	Denmark
2	LINC	Lyngby	Denmark
3	AVENUE	Copenhagen	Denmark
4	Auto.Bus – Seestadt	Vienna	Austria
5	Digibus® 2.0	Koppl (Salzburg)	Austria
6	SHOW	Tamper	Finland
7	GACHA	Helsinki	Finland
8	FABULOS	Gjesdal	Norway
9	Autonomous e-ATAK	Stavanger	Norway
10	Ruter	Oslo	Norway
11	Iseauto	Tallinn	Estonia
12	FABULOS	Lamia	Greece
13	FABULOS	Helmond	Netherlands
14	Gacha	Hämeenlinna	Finland
15	Navetty	Les Mureaux	France
16	Medical Campus	Toulouse	France
17	CNTS	Châteauroux	France
18	Île-de-France	Montigny-le-Bretonneux	France
19	NIMFE	Giverny	France
20	Rouen Normandy Autonomous Lab Project	Rouen	France
21	Paris-Saclay Autonomous Lab	Massy	France
22	NAVLY	Lyon	France
23	ioki Bad Birnbach	Bad Birnbach	Germany
24	EVA-Shuttle	Karlsruhe	Germany
25	HEAT (Hamburg Electric Autonomous Transp)	Hafencity, Hamburg	Germany
26	Autonomous Shuttle Fleet on Public Roads	Monheim am Rhein	Germany
27	KelRide	Kelheim	Germany
28	BeIntelli	Berlin	Germany
29	Olli	Turin	Italy
30	Ohmio LIFT AV Shuttles	Luxembourg City	Luxembourg
31	Avenue	Luxembourg City	Luxembourg
32	SmartShuttle	Sion	Switzerland
33	Robi	Saas-Fee	Switzerland
34	TPH Mobility	Thônex	Switzerland

Table 3-3, continued

	Program Name	**City**	**Country**
35	CityMobil2	Lausanne	Switzerland
36	Ride the Future	Linköping	Sweden
37	Autopilot in Barkarby	Barkarby	Sweden
38	CAVForth	Edinburgh	UK
39	Sunderland Advanced Mobility Shuttle (SAMS)	Sunderland	UK
40	Harlander	Belfast Harbour	UK
41	T-CABS (Trumpington to Cambr. Auton. Bus Serv.)	Cambridge	UK
42	IRIZAR Autonomous bus	Málaga	Spain
43	Nevelo	Kraków	Poland

Examining different pilot projects is useful in identifying the challenges and limitations that AVs can face during operation. Additionally, such analysis provides insights into essential considerations that should be accounted for in implementations. These may include understanding the environmental characteristics within which AVs can operate or the capabilities of different AV brands. Such studies are pivotal to ensuring a safe, efficient, and adaptable deployment of AVs in diverse conditions. The study of different pilot projects demonstrates the flexible application of AV technology across various environments and community needs, with the primary purpose of enhancing connectivity within local transportation networks and improving accessibility. In addition to multiple use cases, different AV brands have been utilized in these projects, including Lexus, Polaris, NAVYA, EasyMile, Local Motors, and May Mobility. Among them, the NAVYA ARMA and EasyMile EZ10 shuttles are the most frequently used. Considering the operating environment and routing model, mixed traffic and point-to-point routing are the most common. Some projects reported that the pilots could successfully navigate a mixed traffic environment (i.e., a mix of conventional vehicles, pedestrians, and bicyclists encountered along the path of the AV), while others mentioned this kind of environment as a cause of disengagements, such as unpredictable movements of vehicles, pedestrians, and cyclists. In addition to traffic-related factors, AV disengagements can result from environmental conditions, obstructions, manual interventions, programming issues, technical limitations, and errors. Among these, environmental and weather conditions, along with programming issues, are the most common causes of disengagements.

Different metrics can be used to evaluate the performance of AV deployment, such as total ridership, average daily ridership, operating speed, number of incidents, and the percentage of time AVs operated in autonomy mode. Among these, Arlington Rapid and Little Roady reported the most significant daily ridership. However, some pilots only reported total ridership, which may not be a good measure of performance due to varying deployment durations. Generally, the operating speeds of all the shuttles were significantly low, causing discomfort for other drivers.

The detailed information regarding these projects' deployment is presented in Table 3-4, Table 3-5, and Table 3-6. Table 3-4 describes the general characteristics of different pilot projects, Table 3-5 compares operational metrics for these projects, and Table 3-6 evaluates them according to their technical performance.

From an operating environments perspective, those environments that include vulnerable road users such as pedestrians and cyclists present significant operational hurdles for AVs. For instance, in the Campus Automated Shuttle case study (Table 3-4, Table 3-5, Table 3-6), the shuttle operated along walkways which resulted in frequent disengagements due to the presence of pedestrians. Similarly, the Yellowstone project resulted in numerous disengagements due to the unpredictable movements of pedestrians in parking areas, highlighting that shuttles perform best on roadways as opposed to pedestrian-dense or parking lot environments. The Wright Brothers National Memorial case study further illustrated this challenge, where the shuttle had to proceed slowly, following pedestrians due to safety protocols, underscoring the impact of pedestrian presence on shuttle speed and efficiency. Moreover, navigating mixed traffic environments with intersections demands robust communication for smooth operation, as evidenced by the Rådhusgata case study, which encountered challenges at intersections without adequate communication. It was also mentioned in this study that parked vehicles detected as obstacles contributed to shuttle slowdowns or stops. While shuttles seem to operate more efficiently on roadways devoid of pedestrian interaction or parking areas, their typically low operating speeds (often 5-8 mph compared to a design speed of 15 mph) can cause discomfort among other drivers. This discomfort can lead to overtaking maneuvers, further complicating shuttle operations in mixed traffic with the presence of high-speed vehicles, a phenomenon observed in the Gainesville AS pilot project.

Table 3-4. Selected pilot projects and their general characteristics

Pilot Name	Location and Service Area	Partners	Date Launched and Duration	Use Case	AVs in Service
Arlington Rapid	Arlington, Texas Central Arlington	The City of Arlington, University of Texas at Arlington, Via.	March 2021- March 2022	Downtown and cross-campus mobility	4 Lexus RX 450h hybrid-electric SUVs 1 fully electric Polaris GEM
Move Nona	Southeast Orlando's Lake Nona Community	Florida DOT (FDOT), Beep, Tavistock, Lake Nona, University of Florida Transportation Institute (UFTI).	September 2019 - September 2022	Suburban community	20 AV electric shuttles NAVYA and Olli by Local Motors
First Phase: City of Las Vegas Second Phase: GoMed	Las Vegas, NV	City of Las Vegas, Regional Transportation Commission of Southern Nevada (RTC), Keolis North America, AAA Northern California, Nevada, and Utah	November 2017- June 2019	First Phase: Downtown (0.6 mile, 3 stops) Second Phase: Connecting downtown and the medical campus (4.5-mile)	First Phase: 1 NAVYA ARMA electric shuttle Second Phase: 4 NAVYA ARMA electric shuttles
Gainesville AS pilot (2 phases)	Gainesville, FL	CoG, FDOT, UFTI, Transdev-North America.	July-August 2018 (First Phase) February-April 2021 (Second Phase)	First Phase: Limited portion of downtown Second Phase: Depot Park to the University of Florida campus	1 EasyMile EZ10 Shuttle
Campus Automated Shuttle Service Deployment Initiative	USF Tampa campus	National Center for Transit Research, FDOT, USF Center for Urban Transportation Research, and Tampa Bay Stakeholders.	February 11-15, 2019	Connecting the USF Library and the Campus Recreation Center (0.45-mile roundtrip)	COAST P1 electric shuttle

Table 3-4, continued

Pilot Name	**Location and Service Area**	**Partners**	**Date Launched and Duration**	**Use Case**	**AVs in Service**
The Electric Driverless Demonstration in Yellowstone (TEDDY)	Yellowstone National Park	U.S. DOT, Xanterra Parks and Resorts, Montana State University (MSU), Beep, Local Motors, Robotic Research LLC.	June-August 2021	1.5-mile route Connecting Visitor Services area and the lodge area (1.5-mile, 3 stops Connecting the main parking area and the campground (1.6 mile, 4 stops)	2 Local Motors Olli shuttles
Connected Autonomous Shuttle Supporting Innovation (CASSI)	Wright Brothers National Memorial	North Carolina DOT (NCDOT), National Park Service (NPS), U.S. DOT, EasyMile, Transdev, TransLoc.	April-July 2021	Loop through Wright Brothers National Memorial (1.5 miles, 2 stops).	1 EasyMile EZ10 shuttle
Smart Colombus-Scioto Mile	City of Colombus	U.S. DOT, City of Colombus, May Mobility	December 2018-September 2019	Served attractions and cultural resources area.	6 electric May Mobility shuttles
Smart Colombus-Linden LEAP	City of Colombus	U.S. DOT, City of Colombus, EasyMile (Linden).	February 2020 (two weeks)	Connection to transit in Linden	2 electric EasyMile shuttles
Little Roady Autonomous Vehicle	City of Providence	Rhode Island DOT (RIDOT), City of Providence, Quonset Business Park (QBP), 3x3, Stae, Star City Group, Brown University.	May 2019- March 2020 (May Mobility) March 2020- June 2020 (RIPTA)	Providence Station and Olneyville Square (loop route, 5 miles, 12 stops)	1 electric May Mobility shuttle 1 electric RIPTA shuttle
Rådhusgata in Oslo	Rådhusgata street, Oslo, Norway	Institute of Transport Economics (TØI), RUTER, Norwegian Public Roads Administration (NPRA, SVV), Oslo, Holo (the operator of AVs)	June 2020- September 2020	Study the performance of AVs in signalized intersections (1.4-km)	1 NAVYA ARMA electric shuttle

Table 3-4, continued

Pilot Name	Location and Service Area	Partners	Date Launched and Duration	Use Case	AVs in Service
Relay	Fairfax, Virginia	Virginia Tech Transportation Institute (VTTI), Fairfax County, Dominion Energy, Virginia DOT, Virginia DRPT, George Mason University, EDENS	October 2020- May 2021	Connect the Metrorail Station and Town Center	1 Electric EasyMile shuttle
CityMobil2	Trikala, Greece	Robosoft, Induct, Institute of Communication and Computer Systems (ICCS), Università degli Studi di Firenze, EasyMile, City governments of Trikala	November 2015-Febrearury 2016	A 2.4 km (1.5 mile) route connects important points of interest and the city center.	4 EasyMile EZ10 shuttle
Otaniemi	Espoo, Helsinki, Finland	Aalto University, the VTT Technical Research Centre of Finland, the City of Espoo	October 2017–November 2017	A feeder to the transport system, providing a connection between the Otaniemi underground station and the campus area.	1 EasyMile EZ10 shuttle
Barkarbystaden	Barkarbystaden, Stockholm, Sweden	The municipality of Järfälla, Nobina technology, the Region of Stockholm/the traffic administration, Stockholm local traffic (SL), VTI, K2, KTH	October 2018-Planned to operate until 2025	Connect transport hubs and final destinations.	3 EasyMile EZ10 shuttle

Table 3-5. Pilots' operational metrics

Pilot Name	**Operating Environment and Routing Model**	**Total Ridership (Passengers)**	**Average Daily Ridership (Passengers/Day/Shuttle)**
Arlington Rapid	Mixed Traffic / Point-to-point	28,140	162
Move Nona	Mixed traffic / Point-to-point	over 470,000	N/A
City of Las Vegas GoMed	First Phase: Mixed traffic / Fixed route Second Phase: Mixed traffic / Point-to-point	First Phase: 32,827 Second Phase: over 50,000	N/A
Gainesville AS pilot	Mixed Traffic / Point-to-point	N/A	N/A
Campus Automated Shuttle	Walkway / Point-to-point	over 500	N/A
Yellowstone	Mixed Traffic / Point-to-point	10,057	68
(CASSI)	Mixed Traffic / Fixed route	3,380	62.6
Scioto Mile	Mixed Traffic / Fixed route	16,062	59
Linden LEAP	Mixed Traffic / First/last-mile service	50	N/A
Little Roady	Mixed Traffic / Point-to-point	May Mobility: 42,206 RIPTA: N/A	May Mobility: 141 RIPTA: 28
Rådhusgata	Mixed Traffic / Point-to-point	N/A	N/A
Relay	Mixed Traffic / First/last-mile service	N/A	N/A
CityMobil2	Dedicated lane / Point-to-point	Over 12,138	N/A
Otaniemi	Mixed Traffic / First - last-mile service	522	N/A
Barkarbystaden	Mixed Traffic / First - last-mile service	N/A	N/A

Table 3-6. Pilots' technical performance

Pilot Name	Average Operating Speed	Automation Driving Performance	Main Causes of Disruptions.
Arlington Rapid	N/A	• Autonomy mode: 86% • Incidents: Five minors (one caused by operator)	• Manual mode in construction presence • Manual Return at End of Shift Due to Inappropriate Initial Programming • Traffic signals • Manual mode in unprotected turns
Move Nona	Operating speed: 12.5 mph	• Infrastructure readiness: 4.07/5 • Quality of the AV Shuttle model: 5/5	• Hard brake in growing vegetation presence
City of Las Vegas GoMed	Maximum speed: 15 mph Operating speed: 8 mph	• Successfully navigated a mixed-traffic environment • Incident: One (Driver's actions and AV's limited access to manual control).	• Heat weather impacts battery via air conditioning use. • Manual switch at crowded stops; automation can't find alternative stop
Gainesville AS pilot	Maximum speed: 15 mph Operating speed: 5-8 mph	• Pedestrians, bicyclists, and bus riders found the shuttle beneficial compared to regular buses. • Drivers' discomfort due to the shuttle's low speed. • Attitudes toward comfort improved after implementation.	N/A
Campus Automated Shuttle	Maximum speed capability: 15-20 mph in separated lane, 12 mph in mixed traffic Operating speed: 4-6 mph	• Riding comfort: 71% agreed (n= 470). • Navigated mixed traffic, avoiding conflicts. • Adjust distance and direction in the presence of distracted road users.	• Opposite-walk pedestrian, shuttle side. • Same-direction walk, shuttle side. • Same-direction walk, in front of shuttle.

Table 3-6, continued			
Pilot Name	**Average Operating Speed**	**Automation Driving Performance**	**Main Causes of Disruptions.**
Yellowstone	Maximum speed: 25 mph Maximum operating speed: 10-11 mph Operating speed: 3-4 mph	• Full operation: 38 out of the 74 days • Number of daily disengagements: 7.0 per day • Incidents: 2 (caused by other drivers).	• Obstacle detection • Weak signal hindered the AV localization • Operator error • Deviations from the path • Weather condition (rain and heavy wind) • Roadside vegetation • Unpredictable vehicle and pedestrian movements near parking areas
(CASSI)	Maximum speed: 25 mph Maximum operating speed: 9.5 mph Operating speed: 5.2 mph	• Full operation: 46 out of the 54 days • Number of daily disengagements: 10.7 per day	• Service suspensions to the battery issues • Weather conditions (rainfall) • Parking area • Disengagements often due to operator caution
Scioto Mile	Maximum speed: In manual mode 25 mph	• 19,118 miles operation (by 6 shuttles.)	• Harsh weather (snow, fog, or strong winds). • Growing vegetation. • The exhaust from other vehicles in cold season. • Speed reduction in presence of seasonal sun glare.
Linden LEAP	Maximum speed: In manual mode 4 mph (intentionally due to potential safety risk.) Operating speed: 7.1 mph (during two weeks of operation)	• Autonomy mode: Greater than 70%.	• Harsh weather (snow, fog, or strong winds) • Growing vegetation • Abrupt stop due to the exhaust from other vehicles in cold season • Speed reduction in presence of seasonal sun glare
Little Roady	Maximum speed: 25 mph in manual mode; 20 mph in autonomous mode. Operating speed: N/A	• Autonomy mode: Less than one-third for average half-route. • Incident: the AV caused 6, one due to operator error (out of 14)	• Unprotected turns • Construction zones • Heavy traffic and cyclists near shuttle • Emergency vehicles passing and vehicles in bike lanes

Table 3-6, continued

Pilot Name	Average Operating Speed	Automation Driving Performance	Main Causes of Disruptions.
Rådhusgata	Speed capability: 18 km/h (11 mph)	• 170 reactions to other road users (out of 408). • Correct reactions in most of encounters. • No severe conflicts.	• Atypical cyclist positioning near shuttles (especially in left turns) • Roadside parked vehicles • Fast users overtaking shuttle • High-speed vulnerable users near shuttle
Relay	Maximum speed: 12 mph Operating speed: 6-8 mph	• The shuttle cannot operate at level 4 capability. • Number of trigger events: 0.71 per mile. • Number of safety-critical events: 41	• Oncoming traffic • Parked vehicles • Pedestrian presence • Vehicle from adjacent lane • Growing vegetation • Sensor malfunctions • System defects.
CityMobil2	Operating speed: 10 Km/h (6.5 mph)	• Successfully navigated without any incidents of loss of control.	• Deviation from the designated route due to a loss of signal (there was no interaction with other modes of transportation as the operation took place in a dedicated lane)
Otaniemi	Maximum operating speed: 12 Km/h (7.5 mph)	• The shuttle cannot execute complex driving maneuvers independently	• Harsh weather (snowflake, heavy rain, dust) • Flying leaves
Barkarbystaden	Maximum operating speed: 18-20 Km/h (11.2-12.4 mph)	• Buses at SAE Level 4; they still require human oversight in certain situations • Not equipped to operate fully autonomously in all urban environments	• Misalignment of predetermined route with areas of need. • Limitations of initial technology in navigating long distances and high speeds

In the City of Las Vegas, the deployment of the Navya Arma AS, equipped with dedicated short-range communications (DSRC) technology for coordinating movements and interacting with infrastructure, revealed both the potential and challenges of integrating AVs into urban environments. A notable incident occurred when a Navya Arma shuttle, operating a 0.6-mile loop in downtown Las Vegas, was involved in a minor collision with a truck-tractor combination vehicle. The truck was backing into an alley when it struck the shuttle. This incident underscores the importance of developing comprehensive safety protocols and effective communication systems between AVs and their surrounding environment, especially in situations involving interactions with traditional vehicles engaged in unpredictable maneuvers.

In Rådhusgata, Oslo, the ASs exhibited several behavioral patterns and atypical reactions, particularly in their interaction with traffic signals and other road users. A notable challenge for the shuttles was navigating the combination of signal phase changes (from green to red) and unexpected behaviors from nearby road users, leading to prolonged and unforeseen stops. In these instances, the shuttle driver had to assume manual control to continue. Additionally, there were occasions where the shuttle halted without any clear reason or in incorrect response to the presence of nearby road users, such as a car parked in the traffic lane. Despite these issues, no severe conflicts were observed, largely attributable to the shuttles' low speeds and defensive driving approach.

The Little Roady AV pilot in the City of Providence demonstrated both the potential and the challenges associated with the integration of AS services in urban settings. Throughout the pilot, there was a noticeable increase in the utilization of autonomous mode; however, observations indicated that approximately 40% of half-route trips were conducted entirely in manual mode. Throughout the pilot, May Mobility reported a total of 14 incidents, which were analyzed based on their causes and whether the shuttle was in manual or autonomous mode at the time of the incident. Notably, eight of these incidents involved the shuttle being struck by another vehicle while stationary or at an intersection and occurred in both manual and AV modes. The remaining six incidents were attributed to fleet attendant errors while in manual mode (e.g., hitting a curb or rear-ending a parked vehicle), a mechanical breakdown, and an incident involving a collision with a cyclist. From the traffic incident data provided by the Rhode Island Department of Transportation (RIDOT), only one of these incidents was classified as potentially involving an injury. Most incidents took place under dry conditions and during daylight hours, suggesting that environmental factors did not significantly contribute to these occurrences.

The CoG AS pilot project represents a significant step forward in the integration of AV technology within an urban transportation network. The shuttle employed a sophisticated array of sensors, computer vision, and mapping technologies to navigate its route autonomously, with a service operator present for oversight. During its testing period, the shuttle traveled at a speed of 10-12 mph. However, the promised speed was 15 mph. A notable advancement in this deployment is the shuttle's ability to communicate directly with traffic signals, enabling it to make right or left turns independently of human intervention. This was facilitated by the inclusion of an OBU within the shuttle, which interacted with roadside units (RSUs) installed on traffic signal poles. The RSU, positioned on the mast arm pole, transmits signal information to the shuttle, allowing for seamless integration into the traffic system and enhancing safety and efficiency in operation. During the pilot, there was one incident when the shuttle was rear-ended by a car in a roundabout. The project also faced challenges when there were obstructions to road markings or deviations, such as temporary lane re-alignment due to the construction of a restaurant on the route, or tree leaves being blown onto the road. Additionally, the shuttle encountered issues like batteries overheating or getting drained due to weather conditions, and shuttle operations being halted due to malfunctioning sensors, such as a weight sensor.

During the AS pilots at Yellowstone National Park and Wright Brothers National Memorial, operational challenges were evident, with Yellowstone achieving full operation for 38 out of 74 days and Wright Brothers for 46 out of 54 days, impacted by factors such as depleted batteries, adverse weather, and technical issues, leading to significant downtime. The disengagement rate was high. On average, shuttles switched from autonomous to manual control seven times per day, highlighted the need for improvements in battery and electrical systems, especially under high consumption from air conditioning and weather-related suspensions. The comparison between the TEDDY and CASSI pilots, despite data recording differences that preclude direct comparison of disengagement types, showed that CASSI had a more disengagement incidents compared to TEDDY. On average, the CASSI shuttle experienced 10.7 disengagements per day, while the two TEDDY shuttles experienced 7.0 and 6.9 disengagements per day, respectively.

The Lake Nona Pilot, utilizing Navya's Arma shuttle, showcased the application of AV technology within a suburban environment. A notable finding was the lack of free Wi-Fi coverage and the specific issue of 4G/5G connectivity near major stops such as Boxi Park, affecting user experience. The operation of Move Nona shuttles at low speeds (12.5 mph) on predominantly two-lane roadways without dedicated bus bays led to significant traffic delays and frustration among car drivers.

The RAPID AS pilot in Arlington showcased a significant application of Level 4 autonomy, operating in automated mode approximately 90% of the time despite the complex urban environment. This service area presented numerous challenges, including at-grade railroad crossings, unprotected left turns, and high pedestrian and cyclist activity, which necessitated manual operation in specific scenarios.

The project did not report any accidents or collisions but addressed some operational incidents. There were five minor incidents where the vehicles did not perform as expected in automated mode. The causes of these incidents were primarily attributed to the vehicles' lane placement within the detailed route network map. Adjustments were made to the map to ensure that vehicles would maintain a safer distance from the curb in future operations. Additionally, one of the incidents was caused by an AV operator error, which led to retraining all AV operators to adhere to proper protocols, especially at and around passenger stop locations.

The deployment of the Otaniemi driverless shuttle bus in Finland highlighted several technological challenges, particularly the sensitivity of the vehicle's sensors to environmental factors such as snowflakes, heavy rain, dust, and flying leaves, which often caused unnecessary emergency stops by misidentifying these elements as obstacles. This technological issue underscores the need for improved sensor technology and greater system robustness in AVs. Additionally, although no accidents were reported, concerns were raised about the vehicle's ability to handle unexpected situations, such as a child darting in front of the bus. The low operating speed of 12 km/h (7.5 mph), while enhancing passengers' perceptions of safety, was also seen as a potential impediment to traffic flow, suggesting that balancing safety with operational efficiency is critical for the broader adoption of autonomous buses.

The deployment of AS buses in Barkarbystaden revealed several technological challenges that hindered their effective integration into the urban transport system. The algorithms guiding the shuttles were not advanced enough to handle the complexities of the urban environment, making it difficult for them to adjust to varying road conditions and traffic patterns safely and efficiently. Additionally, the digital communication systems were inadequate to support seamless interaction with urban infrastructure, such as traffic signals and other vehicles, complicating their smooth integration into the existing transport systems. Furthermore, the operational speed, often limited to about 20 km/h (12.4 mph), negatively impacted the attractiveness and practicality of the service for covering significant distances or providing timely transportation solutions.

The deployment of AS pilots across various locations has revealed both the potential and the challenges of integrating AV technology into urban and suburban environments. The main findings from this part of the literature review are as follows:

- Operational Efficiency and Challenges:

  Full operation was achieved for a limited number of days across the pilots, with significant downtime due to factors such as depleted batteries, adverse weather conditions, and technical issues. Average daily disengagements indicated frequent switches (e.g., from 6.9 up to 10.7 per day for the Yellowstone National Park pilots) from autonomous to manual control, highlighting areas needed for technological improvement.

- Safety and Incidents:

  Minor collisions and incidents were reported, including shuttles being struck by other vehicles or experiencing operational errors, such as incorrect responses to parked cars or unexpected stops. There were no severe conflicts or injuries reported, most likely due to the defensive driving style and low speeds of the shuttles.

- Technological Integration and User Experience:

Challenges with battery usage and the need for midday charging adjustments were common, pointing to the necessity for better battery and electrical system capacities. The lack of free Wi-Fi and issues with 4G/5G connectivity in certain areas affected the user experience.

- Environmental Adaptability:

  Adverse weather conditions led to service suspensions, indicating that current AS technology is best suited for fair, dry weather conditions and faces limitations in more diverse climates. In addition, environmental elements like falling leaves can obstruct road markings and contribute to operational challenges.

- Interaction with Urban Infrastructure:

  Advanced communication systems allowed shuttles to interact with traffic signals, enhancing safety and efficiency in operation. However, navigating complex urban environments, especially those with high pedestrian traffic, remains a challenge.

3.2 Core Technologies Behind ASs

This part of the literature review delves into the critical components that constitute the foundation of AV technology, highlighting the advancements in perception, sensor technologies, and sensor fusion techniques. The review begins with an analysis of various sensors utilized in AVs and their integration through sensor fusion. The discussion then progresses to advancements in machine learning, specifically focusing on improvements in camera detection and tracking. Additionally, the impact of weather conditions on sensor effectiveness is examined. The second part shifts focus to recent developments in Vehicle-to-Everything (V2X) technology, which enables vehicles to communicate with their surroundings and other vehicles. By examining the processes of AV perception, we aim to shed light on the current state of AV systems, their inherent challenges, and the potential pathways toward their future development.

3.2.1 Workflow Modules of an AV System

The foundational layer of AV technology is its ability to perceive the environment. This capability is facilitated by an array of sensors, including Global Navigation Satellite System (GNSS), Inertial Measurement Units (IMU), cameras, lidars, radars, sonars, and infrared sensors (Hasanujjaman et al., 2023). Each sensor type offers distinct advantages and drawbacks. GNSS provides global positioning albeit with limitations in precision, particularly in urban canyons or areas with dense vegetation. IMUs offer precise measurements of angular rates, linear velocities, and orientation but suffer from drifting over time without external references. Cameras deliver high-resolution visual data critical for object recognition, albeit affected by varying lighting conditions. Lidars excel in generating detailed 3D representations of the environment but are hindered by high costs and sensitivity to environmental conditions. Radars are robust against poor weather conditions and excel in long-range detection but offer lower resolution. Sonars, while cost-effective and useful in close-range detection, are limited by their range and resolution. Infrared sensors provide valuable data in low visibility conditions but are constrained by range and ambient temperature variations. Table 3-7 summarizes the advantages and disadvantages of different types of sensors.

Table 3-7. Advantages and disadvantages of different sensor types

Sensor Type	**Advantages**	**Disadvantages**
GNSS	Provides approximate location with a global reference.	Limited accuracy, especially in urban canyons or under dense foliage.
IMU	Measures angular rates, linear velocities, and orientation accurately.	Drift over time without external reference.
Camera	High-resolution visual information, good for object recognition and classification.	Affected by lighting conditions and visibility issues.
Lidar	Provides high-resolution 3D maps of the environment. Good for detecting obstacles and road features.	High cost, limited by low reflectivity surfaces, and weather conditions.
Radar	Effective at long-range detection, velocity measurement, works well in poor weather.	Lower resolution than lidar, difficulty in distinguishing between objects close together.
Sonar (Ultrasonic Sensors)	Low cost, effective at short-range detections. Good in tight spaces.	Limited range and resolution compared to lidar and radar.
Infrared (IR) Sensors	Good for detecting thermal signatures, works in darkness.	Limited range, affected by ambient temperature variations and objects.

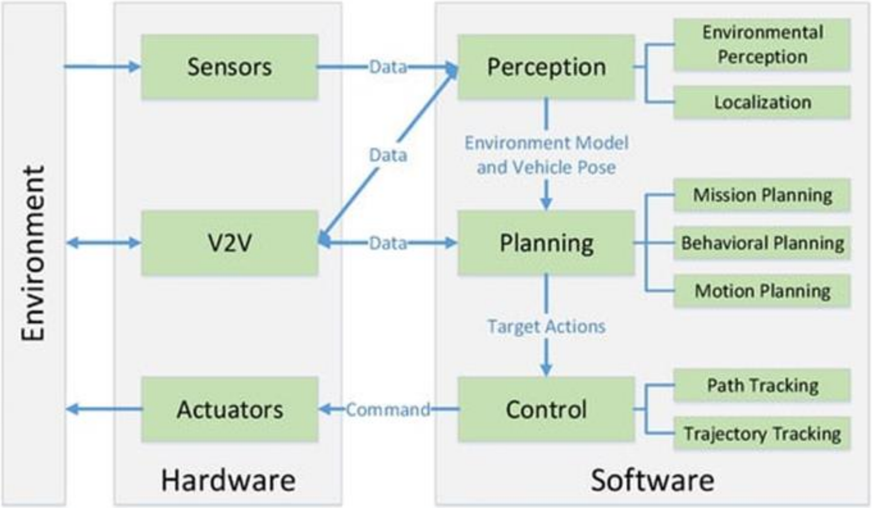
Given the heterogeneous data produced by various sensors, AV systems employ sensor fusion algorithms to integrate this information, thereby creating a comprehensive and accurate representation of the vehicle's surroundings. This process is crucial for mitigating the inherent limitations of individual sensors and for enhancing the reliability of the perception system.

With a coherent perception of the environment established, AV systems proceed to the path planning stage, where algorithms generate safe and efficient routes. This process involves real-time analysis to adapt to dynamic conditions, such as traffic changes, obstacles, and road signs, ensuring optimal path selection for short and long-range navigation.

The final step involves executing the planned paths through precise motion control mechanisms. This includes not only the fundamental task of steering, accelerating, and braking but also managing auxiliary functions such as door operations. Safety measures, including emergency braking and obstacle avoidance systems, are integral to this phase, providing direct interventions to mitigate risks and enhance passenger safety.

Figure 3-4 illustrates the workflow of various modules within an AV system.

Figure 3-4. Modules workflow of an AV system



Source: Adapted from Pendleton et al., 2017

3.2.2 Sensor Blind Spots

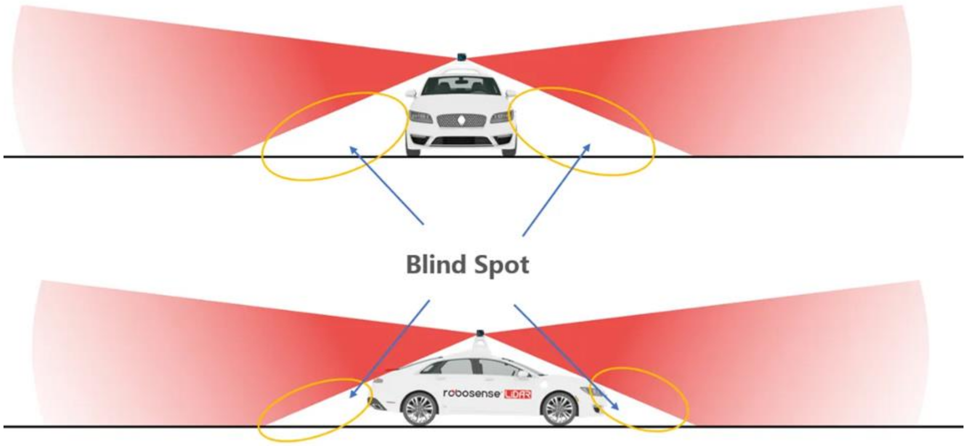
Blind spots in ASs represent a critical challenge that directly impacts their safety and reliability. Despite significant advancements in sensor technology and data processing algorithms, certain areas around the shuttle, known as blind spots, may remain undetected by the vehicle's perception system. Understanding and addressing these blind spots is crucial for the development of reliable and safe AV systems. The primary blind spot areas typically found around an AS are:

Directly Behind or in Front of the Vehicle: Some sensor configurations, especially those relying heavily on lidar and cameras, may have a narrow field of view that misses objects immediately behind or in front of the vehicle's bumper, particularly if the sensors are mounted higher up on the vehicle. (Gu & Chhetri, 2021; University of Florida Transportation Institute, 2022)

Near the Rear Corners: Sensors mounted on the vehicle's sides or rear may not fully cover the areas immediately behind and to the sides at the rear corners. This blind spot can be particularly problematic when reversing or during maneuvers such as lane changes. (Bogdoll et al., 2022; Gu & Chhetri, 2021; Heidecker et al., 2021)

At the Vehicle's Edges: The peripheral areas around the vehicle's front and rear ends, particularly at the edges, can present detection challenges. This is due to the angular blind spots created by the positioning and field of view of side-mounted sensors. (Allidina et al., 2022; Bogdoll et al., 2022; Gu & Chhetri, 2021; Heidecker et al., 2021)

Figure 3-5. Most common blind spots in an AV. The red area highlights the detectable area of the lidar.[1]



3.2.3 Optimal Sensor Placement

The use of lidars and their optimal placement is one common approach to mitigate the blind spots. Figure 3-6 presents the sensor locations on AVs and their intended tasks. Dybedal and Hovland (2017) have developed an innovative approach for determining the best placement of 3D sensors, considering the sensor's range and field of view. This method involves segmenting the targeted area into smaller cubic segments, each characterized by both a boolean and a continuous variable. Such a configuration can be adapted to various situations requiring coverage of specific areas by multiple sensors. Meadows (2019) presented a system equipped with three

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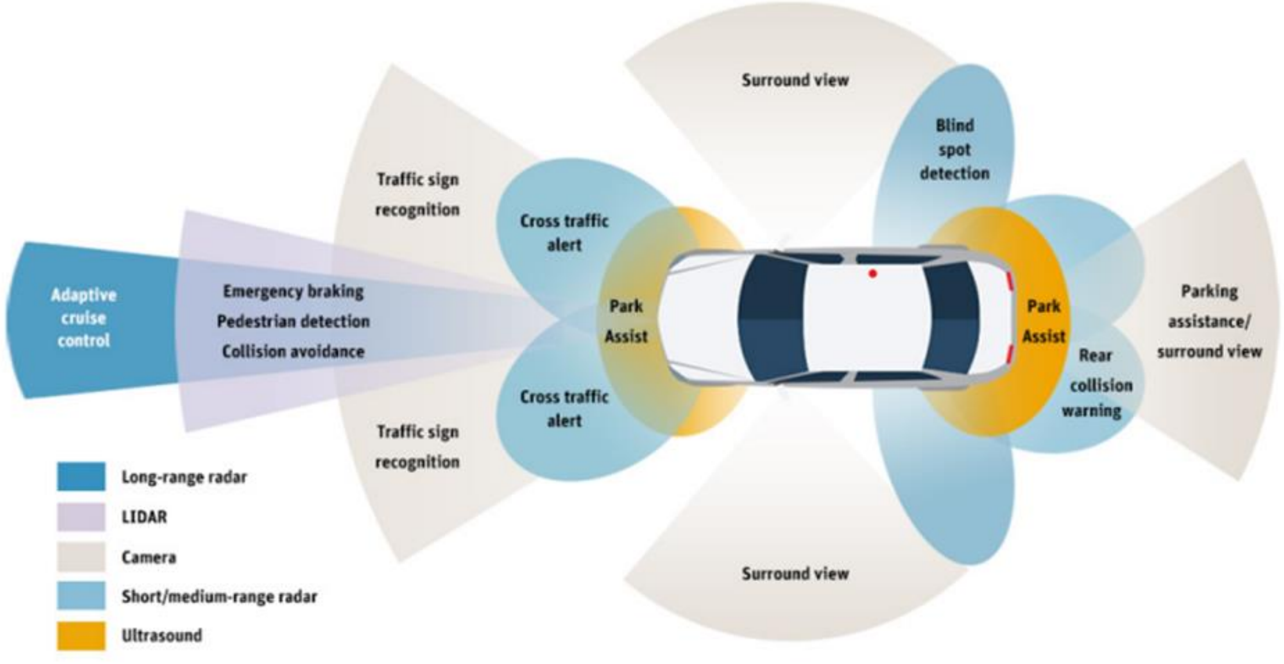
[1] Adapted from https://robosense-pr.medium.com/threeways-for-autonomousvehicles-near-field-detection-of-blind-spots-83b25012d27e)

lidar sensors, utilizing neural networks to assess the efficiency of different lidar positions. Meanwhile, in Kim & Park (2020), the issue of blind zones was approached by employing an occupancy grid framework, leading to the development of a generic algorithm designed to enhance lidar placement configurations. Another research approach addresses the issue of lidar placement by focusing on enhancing the density of the point cloud surrounding the vehicle, a metric assessed using lidar Occupancy Boards (LOB). By defining lidar Occupancy as an objective function, a genetic algorithm is employed to refine this placement optimization. This technique is scalable, suitable for optimizing configurations involving several lidars. Furthermore, for setups with multiple lidars, the Normal Distributions Transform (NDT) scan registration algorithm is utilized to achieve a more accurate alignment, particularly aligning subsequent lidars with an initial or reference lidar.

Another study focuses on finding the optimal lidar arrangement by framing the design process as a problem of min-max optimization. This involves considering the area covered by the lidar's perception and the areas it cannot detect. The paper introduces a novel, biology-inspired metric known as the Volume-to-Surface Area Ratio (VSR) that serves as a straightforward and efficient way to quantify the size of the spaces that the lidar setup fails to detect.

Figure 3-6. Sensor locations on AV and their intended tasks



Source: Adapted from Liu et al., 2019

3.2.4 Multi-Sensor Configuration

Table 3-8 delineates the three primary sensor combinations prevalent in contemporary literature for obstacle detection in AV systems: Camera-Lidar (CL), Camera-Radar (CR), and Camera-Lidar-Radar (CLR). Each combination is evaluated based on its main advantages, practical applications, and overall significance within the realm of multi-sensor fusion systems for environment perception.

According to Wang et al. (2019b) CR sensor combination is the most frequently utilized, offering a blend of high-resolution imaging along with crucial distance and velocity information about surrounding obstacles, with notable implementation by Tesla for enhanced vehicle surroundings perception. Conversely, the CL combination, while providing detailed imaging and precise distance measurements, is less commonly employed compared to its counterparts. Therefore, CLR provides comprehensive environment perception and improved safety redundancy, as it combines the advantages of the three sensors (Wang et al., 2019b; Yeong et al., 2021).

However, this system's complexity introduces hurdles in efficiently combining data from various sources and managing the computational load. A key issue with multi-sensor fusion is the escalating volume of data and the growing complexity of the network architecture, both of which are necessary to enhance recognition accuracy (Wang et al., 2019b; Tsai et al., 2019; Kim et al., 2020)

Table 3-8. Multi sensor configuration

Sensor Combination	**Main Advantages**	**Examples of Use**	**References**
CL	Provides detailed images and precise distance measurements.	Less commonly used compared to CR and CLR because it covers a shorter detection range.	Yeong et al., 2021
CR	Offers high-resolution images along with distance and velocity information of obstacles.	Tesla employs CR and ultrasonic sensor combination for vehicle surrounding perception.	Tesla[2]
CLR	Combines the benefits of both CL and CR, offering greater range resolution, detailed environmental perception through lidar point clouds, and depth map information, enhancing safety redundancy.	Waymo and Navya utilize CLR for environment perception in their AVs.	Navya[3]

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[2] https://www.tesla.com/en_IE/autopilot

[3] https://navya.tech/fr

In addition to the more commonly discussed sensor combinations for AVs, the literature includes some less frequent but innovative configurations that cater to specific sensing needs. One such example is the Radar-Lidar (RL) combination, as mentioned in the study by Asvadi et al. (2018). This pairing takes advantage of both radar's robustness in adverse weather conditions and lidar's high-resolution spatial mapping to enhance vehicle perception capabilities.

Another rare configuration involves the integration of MMW-Radar with an infrared camera, as detailed in Ma et al. (2020). This setup is aimed at augmenting thermal imaging capabilities, allowing for the detection of heat signatures which can be crucial for identifying living organisms or other warm objects in the vehicle's environment.

3.2.5 Traditional and Machine Learning Approaches for Sensor Fusion

The integration of machine learning algorithms for sensor fusion is another effective method for addressing the issue of blind spots in AVs. This approach leverages the capabilities of advanced computational models to intelligently combine data from multiple sensors, thereby providing a comprehensive and accurate representation of the vehicle's surroundings. According to Fayyad et al., 2020 the techniques/algorithms for sensor fusion are categorized into two broad types: the traditional sensor fusion algorithms and sensor fusion algorithms based on deep learning. Traditional algorithms include methods grounded in knowledge, statistical theories, and probabilistic frameworks, which leverage the theories of uncertainty from data imperfections (Gruyer et al., 2017; Van Brummelen et al., 2018). For example, a novel system designed for real-time detection and navigation of a wheeled mobile robot around roundabouts leverages a unique "Laser Simulator" algorithm for object detection, complemented by decision-making processes based on knowledge-driven fuzzy logic (FL) algorithms (Ali et al., 2020).

Machine learning algorithms, particularly Convolutional Neural Networks (CNN) and Recurrent Neural Networks (RNN), play a crucial role in enhancing perception systems. A significant breakthrough in this area was the introduction of the YOLO (You Only Look Once) detector in 2016, which provides a single-stage detection process that combines bounding box prediction and class probability assessments in one neural network pass, achieving detection speeds of 45 FPS and an average precision (AP) of 59.2% on the VOC 2007 dataset (Redmon et al., 2016). The evolution continued with YOLOv4, introduced in 2020, which further refined the model to deliver state-of-the-art performance on the MS COCO dataset, achieving detection speeds of approximately 65 FPS and 43.5% AP on an NVIDIA Tesla V100 GPU. This balance between speed and accuracy sparked considerable research interest. For instance, Wang et al. (2022) enhanced YOLOv4 for greater accuracy and real-time operation, improving AP on the KITTI and BDD datasets significantly, while also boosting inference speed. Zhou et al. (2022) introduced MobileYOLO, a variant optimized for speed and size, achieving a remarkable accuracy rate on the KITTI dataset, with substantial reductions in model size and parameter count. Shortly after YOLOv4, Ultralytics released YOLOv5, which demonstrated real-time detection capabilities with an average processing time of 0.02 s, and an inference speed of the training model reaching 50 FPS (FPS>30 in real-time detection) (Jin et al., 2022). Further advancements by Wu et al., 2021 introduced Yolo v5-Ghost, optimizing the structure for embedded devices with a notable balance between detection accuracy and speed. Most recently, Jia et al. (2023) reported improvements to YOLOv5 using structural re-parameterization, achieving unprecedented accuracy and speed on the KITTI dataset.

3.2.6 3D Object Detection

3D object recognition offers significant improvements over traditional 2D detection techniques by providing a more detailed understanding of the environment, which leads to enhanced detection capabilities. Unlike 2D methods, which overlook the depth aspect of images and thus compromise accuracy, 3D recognition incorporates depth perception. This addition of depth information results in a more accurate and reliable detection process (Gashemiah & Kashef, 2022). VoxelNet, introduced in 2018, presents a groundbreaking single-stage, end-to-end network that transforms point clouds into 3D voxels using a novel voxel feature encoder (VFE) for streamlined feature extraction and 3D bounding box regression (Zhou & Tuzel, 2018). Following this, PointRCNN in 2019 extends 3D detection by leveraging raw point cloud data through a two-stage process, starting with PointNet++ based segmentation for proposal generation, then refining these proposals in canonical coordinates, albeit with a noted slow inference time (Shi et al., 2018). Addressing previous challenges, PV-RCNN, unveiled in 2020, combines 3D voxel CNNs with PointNet-based set abstraction, introducing a voxel set abstraction (VSA) mechanism for efficient computation (Shi et al., 2020). Deep MANTA, proposed in 2021, adopts a template-matching strategy using a library of CAD models to match 2D detections to 3D models, aiming to determine the object's 3D orientation and location from monocular images (Chabot et al., 2017).

3.2.7 Sensors' Vulnerability in Weather Conditions

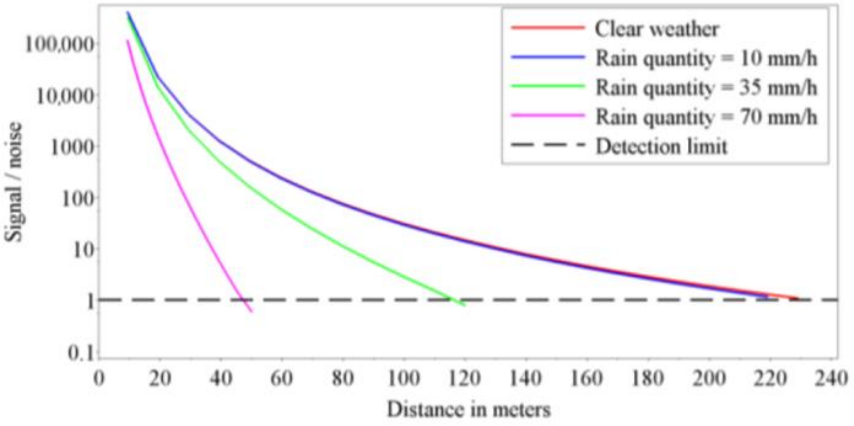
Under optimal conditions, the sensor technology equipped in AVs is designed to accurately perceive the environment and execute the required actions. However, the performance of these sensors and the algorithms processing their data can be significantly compromised by challenging weather conditions.

Precipitation, whether in the form of liquid or frozen water, descends to the ground after forming in the cooler layers of the atmosphere. The size and spread of these droplets determine the precipitation's intensity, measured in millimeters per hour (mm/hr). This intensity impacts how electromagnetic (EM) signals travel through the atmosphere, particularly when it comes to precipitation.

According to Mie scattering, as derived from Maxwell's equations, EM wavelengths that are close to or smaller than the 6 mm droplet diameter are particularly affected (Acharya, 2017). Mie scattering influences EM signal propagation in two primary ways: EM energy is absorbed by water droplets and vapor, leading to signal attenuation. This means the signal strength diminishes as it passes through the precipitation, potentially reducing the sensor's ability to accurately detect objects or the environment (Acharya, 2017). The scattering of EM signals off rain droplets can cause false alarms or obscure real objects from the sensor's detection capabilities. This phenomenon, known as rain clutter, can make it challenging for sensors to distinguish between actual targets and the interference caused by the precipitation (Acharya, 2017).

In clear conditions, lidar systems operating at specific wavelengths (905 nm and 1550 nm) are expected to have a visibility range of up to 2 kilometers. However, in the presence of light rain, at a rate of 2 mm/h, the visibility ranges for these wavelengths are reduced to approximately 1.2 km for the 905 nm wavelength and 0.9 km for the 1550 nm wavelength. As the intensity of the rain increases to 25 mm/h, the visibility range decreases further to 0.7 km for the 905 nm wavelength and 0.45 km for the 1550 nm wavelength. Despite these challenges, within the shorter range of 250 meters, which is typically the operational range required for rangefinders in AVs, the effect of rain on lidar performance is not as pronounced. It's only at higher rain rates that the susceptibility of lidar to rain becomes more evident (Wojtanowski et al., 2014).

Figure 3-7. Variation of the signal-to-noise ratio as a function of the rain rate and distance between lidar and target for a rain droplet radius equal to 3 mm.



Source: Adapted from Hadj-Bachir & de Souza, 2019

The presence of adherent raindrops on the lenses, lens coverings, or windshields of cameras in AVs creates a significant distortion effect on the captured images. The raindrops stick to the surface, forming occlusions that do not completely block the view but instead act like secondary lenses, distorting the light that passes through them. This distortion can heavily impact the camera's ability to accurately perceive and interpret the scene in front of it. You et al. (2015) highlights that the distortion caused by a single adherent raindrop is akin to the effect produced by a fish-eye lens, where the scene viewed through the droplet appears contracted. This contraction effect means that objects or the scene behind the droplet seem smaller and curved.

Moreover, the motion of objects seen through a raindrop appears significantly slower than it does in other parts of the image, by an order of 20 to 30 times.

The 77 GHz RADAR systems utilized in AVs exhibit a relatively minor effect of attenuation due to rain at short distances, with attenuation rates ranging from 0.0016 dB/m for light rain (1 mm/h) to 0.032 dB/m for heavy rain (100 mm/h). Despite this minimal attenuation, rain backscattering significantly impacts 77 GHz RADAR systems. Particularly, the presence of rain increases the amount of backscatter that a RADAR system receives, which can effectively reduce the system's ability to detect and accurately range distant objects.

The study by J. Wojtanowski et al. (2014) demonstrates the significant impact of fog on sensor signal attenuation, highlighting that visibility which should ideally be 0.5 km, drops to around 0.20 km and 0.12 km for wavelengths of 905 nm and 1550 nm, respectively, despite these wavelengths having equivalent maximum range capabilities under clear conditions. The study quantifies the attenuation effect of fog, noting that moderate continental fog can lead to Near-Infrared (NIR) signal attenuation up to 130 dB/km, while heavy maritime fog can cause attenuation up to 480 dB/km.

The influence of fog on various sensors used in AVs can be understood as follows:

- For RADAR Systems: While fog can cause slight Rayleigh scattering on millimeter waves, due to the substantial difference in size between fog particles and the wavelength, the direct impact on RADAR signals is minimal. However, fog can indirectly impact RADAR functionality if it condenses on the RADAR's protective covering or the target, affecting signal transmission and reception similarly to the discussed effects of precipitation.
- For Cameras: Optical cameras are significantly affected by fog due to Mie scattering, given that their operating wavelengths (400–750 nm) are much smaller than the size of fog particles. A study conducted in a fog chamber with fog particles sized 2 microns and 6 microns revealed that visibility for cameras could reduce to 30 m from an ideal range of 60 m (Zhang et al., 2019).

Ultrasonic sensors, which use sound waves to detect objects and measure distances, are impacted by humidity due to the way moisture in the air affects the propagation of sound.

The impact of humidity on attenuation is not uniform across all frequencies used by ultrasonic sensors. For instance, at a frequency of 200 kHz, maximum attenuation occurs when the air is fully saturated with moisture (100% relative humidity). However, at lower frequencies, such as 60 kHz, which is closer to the frequencies used by modern AV sensors, maximum attenuation is observed at lower relative humidity levels, around 60%. This suggests that the optimal performance of ultrasonic sensors may vary significantly depending on their operating frequency and the ambient humidity. The interaction between temperature and humidity also affects the operation of ultrasonic sensors. For example, Gultepe (2007) observed a high increase in attenuation at 20°C, with changes in humidity.

3.2.8 V2X Communication

V2X communications may significantly advance road safety, traffic management, and enhance the driving experience. The choice of communication mode can vary based on the specific service or application in question. Communication mode options are as follows:

- Vehicle-to-Network (V2N) Communication: This mode involves communication between a vehicle and a V2X application server, typically over a cellular network such as Long-Term Evolution (LTE). It facilitates a variety of services including infotainment, traffic management, navigation, and enhanced safety features. (Chen et al., 2017; Martín-Sacristán et al., 2018).
- Vehicle-to-Infrastructure (V2I) Communication: In V2I communication, vehicles communicate with roadside infrastructure, such as RSUs. This approach is primarily used for broadcasting safety messages to drivers within the range of an RSU and for exchanging information at intersections to prevent collisions.
- Vehicle-to-Vehicle (V2V) Communication: V2V enables direct communication between vehicles to support cooperative driving. This includes the exchange of information for collision warnings, lane change assistance, and alerts about approaching emergency vehicles.
- Vehicle-to-Pedestrian (V2P) Communication: V2P communication establishes a direct link between vehicles and vulnerable road users (VRUs), such as pedestrians and cyclists, to enhance road safety. It alerts both parties to potential collision risks, aiming to prevent accidents.

Wang et al. (2019a) delineates the standard components of a V2X system, comprising vehicle communication devices (OBUs), pedestrian communication devices (such as smartphones or body-mounted sensors), infrastructure/roadside sensing units (RSUs), and information processing units (IPU), located either on edge devices or servers.

At the forefront of V2X communication benefits is its ability to significantly augment safety and navigation (Edwertz, 2017). Through enabling comprehensive communication between vehicles (V2V), infrastructure (V2I), pedestrians (V2P), and networks (V2N), V2X technologies achieve a 360-degree environmental perception (Yusuf et al., 2024). This holistic approach to sensor coverage critically reduces collision risks and navigational errors, especially in scenarios where visibility is compromised or in complex driving conditions. The deployment of real-time, high-definition maps and an extensive array of sensor data underscores the indispensable role of V2X technologies in providing the precision required for AV navigation and reliable obstacle detection.

The reliability of V2X communications, especially in scenarios marked by high vehicular density and mobility, is significantly bolstered by the architectural enhancements inherent in the Cellular Vehicle-to-Everything (CV2X) standards. This reliability is paramount in safety-critical automotive applications, where timely and secure transmission of messages can decisively mitigate collision risks and enhance road safety, demonstrating the critical nature of V2X in supporting the foundational elements of road safety.

With the advent of 5G communication reliability and lower latency of V2X communications have significantly improved, facilitating large-scale traffic management and advanced vehicular functionalities (Lianghai et al., 2018). Compared to 4G, which has a latency limit of 20 milliseconds, NR technology is designed to achieve latencies as minimal as 1 millisecond, peak data transmission rates of up to 20 gigabits per second, and widespread transmission rates of 100 megabits per second. For AVs, the critical communication requirements include safety and cooperative driving messages that necessitate latencies below 10 milliseconds. (Abou-zeid et al., 2019)

The transition from the LTE standard in Release 14 to the adoption of 5G and 5G NR in Releases 15 and 16, respectively, marked the introduction of interfaces such as PC5 and LTE-Uu. This evolution facilitated improved diversity gain and expanded communication distances. In their detailed examination of the LTE-V standard, Molina-Masegosa & Gozalvez (2017) highlighted the enhanced performance of CV2X compared to DSRC, especially notable in mode 4. This mode, which does not rely on cellular infrastructure, supports V2V and V2P connectivity, showcasing the advanced capabilities of CV2X in supporting autonomous vehicular communications.

In addressing the complex landscape of V2X communications, it is paramount to consider not only the advantages but also the challenges that accompany the deployment of these advanced technologies. A primary concern within the V2X ecosystem is the high data transmission requirements necessitated by the significant amount of data generated by onboard sensors, cameras, and other devices. The voluminous data flow poses formidable challenges in bandwidth and network capacity, pressing the need for highly efficient data transmission and processing methods. This challenge is further compounded by the complexity and cost associated with adopting advanced video encoding standards such as H.265/HEVC. While these standards are instrumental in achieving efficient data transmission, they introduce a higher level of complexity and, subsequently, potentially greater costs associated with the computational power required for encoding and decoding processes.

Complicating the landscape further are interoperability issues. The quest for seamless compatibility and interoperability among the myriad of V2X applications and technologies spans across different manufacturers and regions, presenting a complex puzzle. This challenge underscores the necessity for a standardized framework that can harmonize the diverse technologies under the V2X umbrella, ensuring a cohesive and interoperable ecosystem.

Moreover, the deployment of V2X technologies is significantly tethered to infrastructure investment. The establishment of a robust V2X communication network necessitates substantial investments in communication infrastructure, including roadside units and network upgrades, especially to support the burgeoning capabilities of 5G. This requirement for heavy upfront investment poses a considerable hurdle in the widespread adoption and implementation of V2X technologies.

Central to the discussion on V2X deployment challenges are security and privacy concerns. The exchange of vast amounts of data, intrinsic to the functioning of V2X systems, raises concerns regarding security and privacy. Robust measures are imperative to safeguard against unauthorized access and cyber threats, ensuring the integrity and confidentiality of the transmitted data.

Lastly, the energy consumption associated with the processing and transmission of data, particularly high-definition video, emerges as a critical concern. This aspect is of particular relevance to electric vehicles, where the energy expenditure on data processing and transmission could impact vehicle range and efficiency.

3.2.9 Summary

This part of the literature review delves into the technological aspects of AVs, spanning from sensor arrays and sensor fusion techniques to the impact of adverse weather conditions on sensor performance and the vital role of V2X communications. Key findings are as follows:

- AV technology relies on a complex interplay of sensors, algorithms, and control systems to navigate autonomously.
- The integration of diverse sensor data through sensor fusion algorithms, coupled with the application of machine learning, significantly enhances the environmental perception and reliability of AV systems.
- Challenging weather conditions such as precipitation, fog, and humidity can notably degrade sensor performance, underscoring the importance of developing weather-resilient sensor technologies for operating the AV Shuttles in weather diverse environments.
- V2X communications are very important for enhancing safety, navigation, and the overall driving experience by facilitating comprehensive environmental perception.
- 5G technology boosts V2X communication reliability and drastically reduces latency to as low as 1 millisecond, essential for real-time decision-making in AVs and enhancing road safety by enabling timely and secure message transmission.

Despite significant advancements in V2X communications, AV technology faces challenges related to high data transmission requirements, interoperability, infrastructure investment, security, privacy, and energy consumption.

3.3 Infrastructure Requirements

While technological advancements can significantly impact the safe and efficient operation of AV shuttles, whether vehicle operations can reach optimal performance is highly dependent on infrastructure elements. Thus, a comprehensive understanding of the impact of the quality of infrastructure on AV operations is crucial in projecting its future use. This section discusses the following infrastructure elements that have been found to affect AV operations:

- Connectivity
- Signage
- Pavement condition
- Type of Highway Facility
  - Intersections
  - Roundabouts
  - Two-lane highways with shared turning middle
- Turning lanes and pockets
- Emergency Stop Area Availability
- Bridges
- Charging stations
- Parking lots
- Overall level and quality of maintenance for all infrastructure elements

3.3.1 Connectivity

AVs navigate the travel path using preloaded maps and using input from sensors such as cameras, radar, and lidar. In many cases the operation of the AV is dependent on the telecommunication network. Additionally, some vehicles communicate with other vehicles and/or the surrounding infrastructure through various communication technologies. In the absence of V2I communication, there would be an essential need for extra signage (National Academies of Sciences, Engineering, and Medicine, 2021). In the Rådhusgata case study (Pokomy et al., 2021), AV shuttles experienced significant disengagements, such as unexpected delays or stops at signalized intersections, while operating without V2X communication. This mirrors the experiences of research teams in the Gainesville and Lake Nona projects. In the Gainesville case study, the shuttle operated independently, utilizing communication with signals (UFTI, 2022). However, in the Lake Nona case study, the safety operator took control of the shuttle and manually navigated through signalized intersections.

In addition, enhancing the road network's communication capability can significantly aid in ensuring safe navigation, especially in confusing areas where the environment brings challenges for AV operations. For example, in a significant crash involving a Tesla vehicle the automated system failed to detect a truck across its path due to glare from the sun. One potential solution could involve equipping the vehicle with connectivity to recognize the presence of another vehicle and prevent such incidents (Finn et al., 2017). Also, the data generated from communicating with infrastructure can be used to identify the reason for each decision an AV makes and for disengagements of the AV operation (Anund et al., 2022). In summary, smooth AV operation requires remote and onboard processing power systems.

Communication with infrastructure can be categorized into three groups: long-range technologies, medium-range technologies, and short-range technologies (Ahangar et al., 2021).

Low data rates and high latency are key characteristics of short-range communication technologies. Those make them unsuitable for applications such as remote driving or remote maintenance. However, they can be used in situations that do not require strict latency, such as warnings for forward collision, toll checks, and vehicle identification (Ahangar et al., 2021).

DSCR, which is one type of V2X communication technology, and Wi-Fi communication, can be categorized as medium-range technologies that support higher mobility and are more flexible. Lane changing assistance (Ahangar et al., 2021), and providing real-time incident and work zone information (Liu et al., 2019) are some applications of these technologies. Klauer et al., 2023, referred to efficient AV operations at intersections as a result of utilizing the traffic Signal Phase and Timing (SPaT) information. This information is gained through different types of communication including:

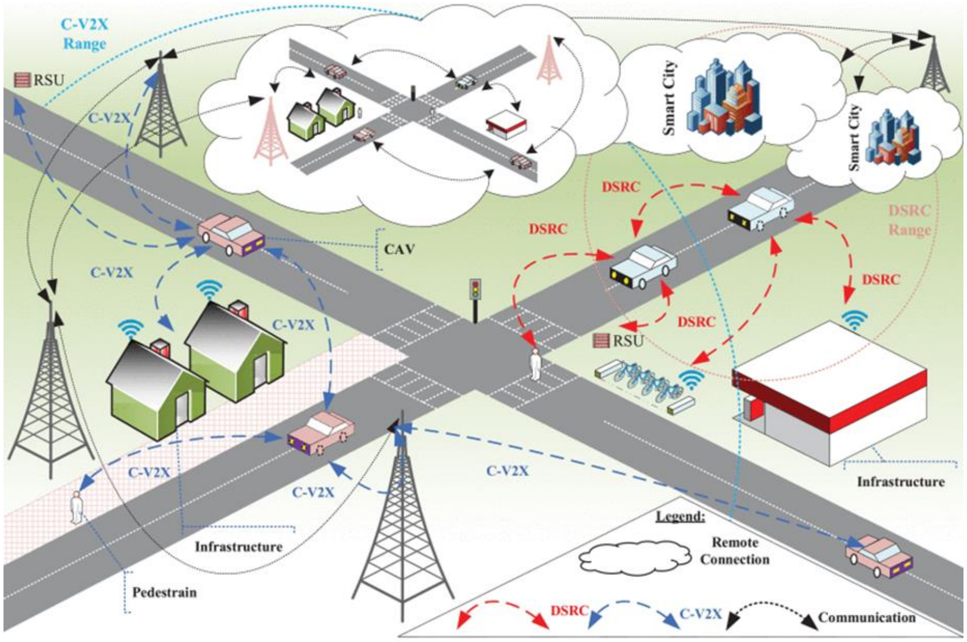
- DSRC RSU which supports the broadcast of SPaT data
- Interfacing the Traffic Signal Controller and the DSRC RSU to control the traffic signal based on SPaT data
- Sending SPaT data from the DSRC RSU to the DSRC Onboard Unit in the AV
- Requesting an extension of the green phase for up to 15 seconds from the Transit Signal Priority (TSP) System to ensure adequate time for the AV to traverse the intersection safely

Long-range technologies, including CV2X technologies, (National Academies of Sciences, Engineering, and Medicine, 2021) and 5G new radio (5G-NR), are pivotal for the future of intelligent transport systems. Generally, high data rates, low latency, and reliable communication are key prerequisites for various vehicular applications. These essential features are provided by 5G-NR technology, as a result of supporting massive Machine Type Communication (mMTC), enhancing Mobile BroadBand (eMBB) and improving Ultra-Reliable Low Latency Communication (URLLC) (Ahangar et al., 2021).

According to Federal Communications Commission's decision in 2020, a significant portion of the auto safety spectrum was reallocated from DSRC to CV2X technologies that make CV2X technology the prevailing standard band for communication (Shepardson, 2022). Common implementations of DSRC and CV2X alongside various connectivity alternatives are depicted in

Figure 3-8. It shows how these technologies can provide vehicles with useful information by offering various connectivity options, such as V2P, V2V, V2I, and V2N.

Figure 3-8. Common implementations of DSRC and CV2X



Source: Adapted from Damaj et al., 2022

AV connectivity can also be discussed based on different types of in-vehicle networks including Local Interconnection Network (LIN), Controller Area Network (CAN), FlexRay, Media-Oriented Systems Transport (MOST), and Ethernet. The LIN has low cost and the easiest deployment and can be used for low-speed communication applications such as battery monitoring and temperature sensors which require low-speed communication. CAN is the most widely used and cost-effective automotive network, known for its moderate fault tolerance. It is commonly employed in engine controllers, transmission units, and climate controllers. FlexRay, although more expensive, provides faster speeds and increased fault tolerance, making it suitable for applications such as chassis control, safety radar, and supplementary restraint systems. The MOST network is designed for high-speed connectivity and optimized for in-vehicle multimedia, navigation systems, and infotainment data transmission. Wired Ethernet provides high-speed capabilities but has limited applications, as it is relatively new in production cars, being used in Electronic Control Unit (ECUs), cameras, and entertainment units. As vehicles incorporate more advanced features such as Advanced Driver Assistance Systems (ADAS) and multimedia functions requiring high bandwidth, there is potential for Ethernet networks to become the primary in-vehicle network in the next generation (Damaj et al., 2022). Therefore, the operation of AVs is highly dependent on communication with the external environment and its internal components. Each of these external and internal elements serves different applications, according to their characteristics and limitations which have been discussed in this section. Thus, considering specific applications, different infrastructure should be implemented to facilitate AV operation.

3.3.2 Signage

For the implementation of AVs it is critical that signage and markings are consistent and clearly visible. To facilitate AV deployment, State and local agencies should standardize all signs and road markings, implement regular maintenance and monitoring procedures (Liu et al., 2019). Figure 3-9 depicts the additional signage that was used in the Yellowstone National Park case study (Cregger et al., 2022) to facilitate AV navigation. These signages acted as reference points in creating a 3D virtual map and improved the vehicles' localization capabilities. It has been suggested in the literature that agencies may consider installing roadside sensors, replacing current signs with machine-readable signs, and implementing machine-readable, radar-reflective road markings. According to Haydin (2019) such enhancements can help AVs predict unexpected situations and ease AV operations, especially at night and in harsh weather conditions. However, this transition hinges on ensuring that all necessary information is both digitally accessible in a reliable manner and legally permissible. Also, the presence of conventional vehicles and other roadway users would require the use of conventional signs and markings. Lastly, the replacement of all signs and markings is expensive for agencies to undertake in a short amount of time. Therefore, despite the recent advances in digital infrastructure, the complete elimination of physical road features is unlikely in the near future (Tengilimoglu et al., 2023).

According to the Wright Brothers National Memorial case study (Cregger et al., 2022), in addition to traffic-related signs, other signage should be placed at stop stations to inform passengers about the location, timing, and duration of AV operations. These can also contain a QR code to direct passengers to a related website for more detailed information.

Figure 3-9. Localization signs as reference points for 3D virtual mapping in AV navigation

Source: Adapted from Cregger et al., 2022

3.3.3 Pavement Condition

AVs operate on the pavement currently used by conventional cars. However, it is likely that AV operations may lead to more frequent maintenance and strengthening of specific areas. Firstly, this may occur because AVs may be more sensitive to pavement distress (Peng et al., 2023). Secondly, the increase in the number of AVs, coupled with the fact that AVs tend to operate in the middle of the roadway (Liu et al., 2019), may lead to an accelerated deterioration of specific areas of the pavement. This operational characteristic, combined with the growing number of AVs, increases the risk of rutting and fatigue processes, contributing to pavement deterioration.

From another perspective, the potential use of pavements as charging infrastructure, and the potential use of pavements for AV navigation may alter their functionality and level of importance. These scenarios are not expected to be implemented in the short-term considering their high costs (Othman, 2021a).

3.3.4 Type of Highway Facility

AVs function differently at various types of facilities. Their operation is particularly affected when they must find a suitable gap. This subsection discusses the effects of different types of highway facilities on AV operation.

3.3.4.1 Intersections

In a Virginia case study (Klauer et al., 2023), the AVs' operation was evaluated at different types of intersections, considering the rates of E-stops[4], soft stops[5], and circumvention[6] events. The highest rates of circumvention and soft stops were observed at four-way stop-controlled intersections. The highest rates of E-stops were observed at T-intersections. These configurations appear to present the most difficulties in AVs' operation compared to other segment types. The rate of safety-critical events[7] at four-way stop-controlled intersections was significantly higher than that at other road section types (Klauer et al., 2023).

A study in Rådhusgata in Oslo (Pokomy et al., 2021) investigated AV operation at three intersections by considering four areas at each intersection: a) before the stop bar, b) crossing the stop bar, c) inside the intersection, and d) past the intersection. The researchers concluded that the turning maneuvers posed greater challenges for AVs compared to through movements. Most

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[4] E-stops events are defined as those occurring when the AVs' safety system executed a hard braking maneuver (averagely 0.3-g deceleration) land bringing the vehicle to a complete stop.

[5] Soft stops are defined as those where human operators manually initiate stops with an average 0.05-g deceleration, aimed at preventing aggressive stops.

[6] Circumvention events happened where the human operators manually took control of the AV and maneuvered around the obstacle that had previously forced the AV to come to a stop.

[7] Safety-critical events encompassed situations in which operators, passengers, or any other road users experienced a crash, near-crash, crash-relevant conflict, or proximity conflict events.

unexpected events, such as inconsistent speed and hard or sudden stops, occurred primarily in the first and third areas.

In the first area, unexpected situations at a distance from intersections included improper reactions to parking vehicles alongside the roadway, or VRUs such as bicyclists. As proximity to intersections increased, the significance of changing traffic signals, occasionally combined with unpredictable VRUs actions, became more pronounced.

In the second area, most of the events were related to right-turning maneuvers, where the shuttle reacted to crossing pedestrians. While most reactions were acceptable, some incorrect responses occurred when pedestrians crossed slightly outside the crosswalk or overtook the shuttles from the left.

In the third area, almost all events were associated with turning maneuvers, often triggered by a pedestrian standing near the crossing or the presence of a cyclist in an unexpected position on the approach. Those events became more severe when the AV got stuck in the middle of the intersection, obstructing other vehicles' operations. In such cases, the safety operator took control of the AVs and manually completed the operation. In several instances, possibly due to traffic signal changes or pedestrians crossing slightly outside the crosswalk, AVs did not yield to those pedestrians.

For the fourth area, the authors report that there were a few events at only one of the intersections, but they were not able to identify the specific reasons.

3.3.4.2 Roundabouts

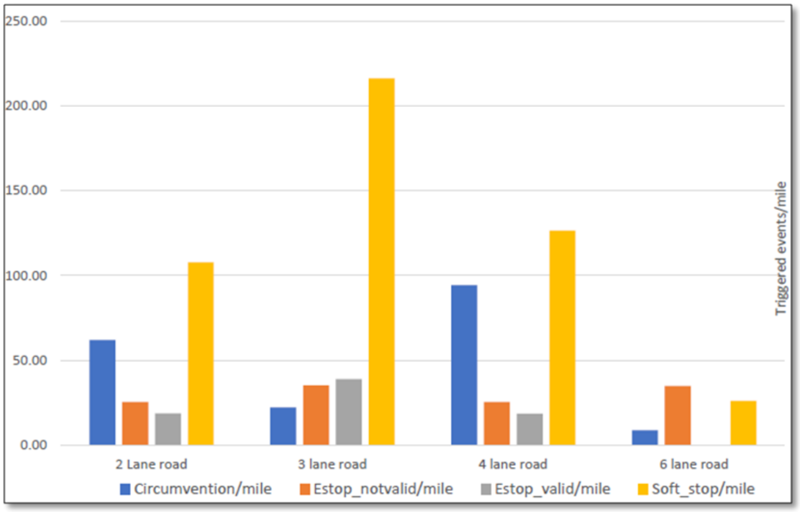
Roundabouts generally mitigate the severity of accidents by converting head-on collisions that occur at other intersections into sideswipe collisions. Liu et al., (2019) report that intersection elements are more predictable, ensuring safer operation for AVs. Godsmark et al., 2015, suggest that as the number of AVs grows, signalized intersections will gradually be replaced by roundabouts. They speculate that roundabouts reduce delay and queuing times, resulting in smoother traffic flow. The authors speculate that such a benefit would be particularly pronounced as a consequence of the AV’s utilization, that can better manage the merging maneuvers between different lanes (Liu et al., 2019). However, microsimulation results (Deluka Tibljaš et al., 2018) indicate that queue length may increase or decrease depending on the geometric design of the roundabout, the geometric standards of the arms, and traffic distribution. Moreover, from a safety perspective, other microsimulation results indicate that the number of estimated crashes may increase as the number of AVs increases.

Also, based on the research team’s experience with the TRANSDEV AV in Gainesville, roundabouts presented a significant challenge, and the operator always had to disengage autonomy when approaching a roundabout. The main issue seemed to be that the autonomy was not able to accurately judge gaps. Therefore, there is an essential need for further investigation to understand the effect of roundabout design standards on AVs' operation.

3.3.4.3 Two Lane Highways with Shared Turning Middle

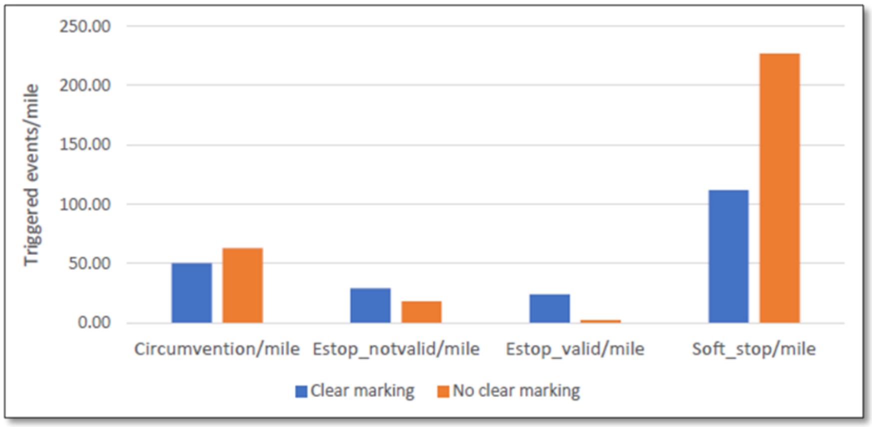
Three-lane roadways (shared turning lane in the middle) have reportedly posed significant challenges in AVs' operation, and they have experienced the highest rates of safety-critical events compared to other types of lane configurations (Klauer et al., 2023). The researchers reported that this is due to the highest rate of soft stops and E-stops observed in this specific lane configuration. The 4-lane, 2-lane, and 6-lane roads are ranked in descending order after the 3-lane configuration. The highest rate of E-stops on three-lane roads was associated with instances where vehicles overtake the AVs and maneuver in front of them. These results are illustrated in Figure 3-10. Considering lane markings, the higher rates of soft stops and circumventions occurred at road sections with no clear markings; road sections with clear markings experienced higher rates of E-stops (see Figure 3-11).

Figure 3-10. Triggered event rates by lane configuration



Source: Adapted from Klauer et al., 2023

Figure 3-11. Triggered event rates by lane marking



Source: Adapted from Klauer et al., 2023

3.3.4.4 Turning Lanes and Pockets

The presence of turning lanes can also present difficulties for the AVs operation. Left turn lanes and left turn movements reportedly had the highest rate of triggered events (Klauer et al., 2023) contributing to a noticeable rise in the rate of soft stops. Conversely, the presence of right turn lanes showed a higher rate for E-stops and safety-critical events (Klauer et al., 2023). According to the authors, operators typically demonstrate greater sensitivity to the left turn maneuvers than the right ones, which may account for the differences in the rates and types of the represented triggered events (Klauer et al., 2023).

3.3.4.5 Emergency Areas

Emergency areas are critical elements for safe AV operation. In the case of vehicle malfunctioning, there should be suitable areas for AVs to stop or restart (Liu et al., 2019). The need for such infrastructure becomes more significant in cities with harsh weather conditions that make AVs face more disengagements. Also, documenting the location of emergency areas is crucial for AV navigation. (Othman, 2021a) suggested two scenarios for handling emergency areas. The first one indicates that as the number of AVs increases the required lateral distance between vehicles could be reduced, leading to narrower lanes. The authors speculate that the remaining space can be used as emergency areas. However, this would be feasible only with 100% AVs in the traffic stream.

The second one considers the potential use of parking lots that may become available and can be converted into emergency areas. In the UK, traditionally, hard shoulders have been used as an emergency area. However, recently, they have been changed into running lanes, which may be misused by drivers (Liu et al., 2019). The authors indicate that the possibility of each of these scenarios, the frequency, and the design standards for emergency areas, require further investigation. Orthman, (2021) recommends that the locations of these areas be mapped and documented to facilitate AVs' navigation towards them as needed.

3.3.4.6 Bridges

Some authors have speculated that bridge design methods may need to undergo significant changes due to the impact of AV platoons. Liu et al., (2019) suggest that there is a need for further investigations to address the effect of platoons on existing bridges, particularly for truck platoons. They indicate that defining specific criteria that should be considered in developing new standards is crucial. They also indicate that one potential alternative for reducing the effect of platoons is to restrict the space between trucks. This is particularly important because, among various factors, this aspect plays a crucial role in the load impact on bridges (Othman, 2021a).

Generally, the deployment of AV truck platoons has been deemed a non-starter for freight companies. The research team did not find any other references regarding bridges and AV shuttles. At this time, there does not seem to be a reason to consider changes to bridge design due to AV presence, as these are not expected to operate in platoons. However, AVs (and other

Electric Vehicles (EVs)) are generally heavier due to the battery weight. Their weight is much lower than that of trucks, but there may be a need to consider AV/EV weight in addition to truck-related weight and impacts.

3.3.5 Charging Stations

AV charging stations are important infrastructure elements which require more attention to ensure effective operation. Battery usage-related challenges can bring serious disengagements in AV operations. One possible solution for this problem is increasing the number of charging stations. In a Yellowstone National Park case study (Cregger et al., 2022), a charging station was added near the operation to make this procedure more efficient (Cregger et al., 2022). When multiple shuttle brands operate on the same site, it may be very difficult to provide all of them with both short and long-term charging (Anund et al., 2022). Constructing charging roads instead of increasing the number of charging stations is a potential effective alternative that has been implemented in Sweden, where AVs can be charged while driving on the road (Liu et al., 2019).

3.3.6 Parking Lots

Many research studies indicate that an increased number of AVs can lead to a reduced need for parking lots. This is attributed to the flexibility of AVs to operate at different times, coupled with the utilization of autonomous valet parking systems. These systems enable AVs to park closely together without the need to account for door space, consequently reducing the required space and the number of parking lots (Othman, 2021a).

According to the literature, in existing parking lots, AVs face challenges in navigating their paths, especially considering the strength of GPS signals (Liu et al., 2019). This issue is particularly prominent in underground parking lots where GPS signals are weak, leading to disruptions in AVs' operation. To address this, there is a need for infrastructure improvement, and one possible solution is to deploy Bluetooth and near-field communication technologies in these areas (Othman, 2021a). In this context, attention must also be given to parking lot entrances, as turning movements at these locations pose challenges for AVs' operation, especially when multiple parking lot entrances converge into a single route section (Klauer et al., 2023).In addition to dedicated AV parking lots, it is advisable to allocate spaces near AV stations for bikes or cars to facilitate trip connections (Peng et al., 2023).

3.3.7 Overall Quality of Maintenance

Maintenance procedures are a crucial element in the operation of AVs (Peng et al., 2023), and they vary across different seasons. In spring, it is essential to cut vegetation alongside the road, control its size, and, in some cases, move it further away from the lane. In winter, the right-of-way should be cleared of snow. Failure to address these situations may lead the AV to detect them as obstacles, potentially resulting in a reduction in speed or complete stops (Anund et al., 2022). As an example, in the case study of the Wright Brothers National Memorial, vegetation longer than the standard size was detected as an obstacle, leading to disengagement of autonomy

(Cregger et al., 2022). Additionally, checking the brightness condition of the road and the clarity of road signs are other factors that significantly impact AV operations by enhancing readability and easing the navigation process (Liu et al., 2019; Peng et al., 2023).

In addition to roadway maintenance, the process of cleaning and maintaining AVs is completely different from conventional vehicles. This is because of the presence of numerous sensitive sensors and hardware, underscoring the significance of special infrastructure to facilitate this cleaning procedure. This need becomes particularly important in the case of cleaning the lidar sensors, cameras, odometers, and the like (Anund et al., 2022).

3.3.8 Summary

This section presents the summary and findings for each of the infrastructure elements examined.

Connectivity

- In the absence of communication, additional signage may be essential for AVs to safely navigate their path. Additionally, some case studies have shown that AVs are unable to operate at intersections without communication.
- Data generated from infrastructure communication may aid in understanding decision-making and AV operation disengagements.
- Communication technologies vary in range and capability, impacting their suitability for specific applications in intelligent transport systems. It is noteworthy that among all available technologies, CV2X is emerging as the dominant standard for vehicle communication.
- In-vehicle networks vary in speed, cost, and application suitability, from LIN 's cost-effectiveness for low-speed tasks to Ethernet's high-speed capabilities for advanced functions like ADAS. Ethernet is poised to become the primary network for future vehicles, given its ability to support high-bandwidth multimedia functions and ADAS.

Signage

- High visibility of signage and infrastructure markings is crucial for AV operation.
- Reference markers can support AV navigation by improving localization through 3D virtual maps.
- Future considerations include roadside sensors, machine-readable signs, and radar-reflective road markings to aid AV, especially in adverse conditions.
- Digital mapping advancements may allow for replacing physical infrastructure with digital alternatives.
- Signage at stop stations should inform passengers about AV operations, location, and timing.

Pavement Condition

- AVs can operate on regular pavements, but more frequent maintenance and strengthening of specific areas are needed due to their sensitivity to pavement distress.
- The increase in the number of AVs, coupled with their tendency to operate in the middle of the roadway, may accelerate pavement deterioration, leading to rutting and fatigue processes.
- The growing importance of charging infrastructure and navigation processes in AV operation could alter pavement functionality, with potential integration of magnets for navigation enhancement and use as charging roads. However, the feasibility of these changes is currently limited by the cost-to-benefit relationship.

Type of Highway Facility

- Intersections
    - Stop sign-controlled four-way intersections and T-intersections posed the most challenges in AVs' operations compared to other intersection types.
    - The frequency of safety-critical events at stop sign-controlled four-way intersections was notably higher than that for other types of intersections.
    - Within intersections, turning maneuvers presented greater challenges for AVs compared to through movements.
    - The majority of triggered events were associated with areas upstream of the stop bars and inside the intersections.
- Roundabouts
    - There are different opinions regarding the potential changes in roundabout design as a result of AV deployment. While some authors state that roundabouts might be changed into intersections to ensure safer operation, others believe that signalized intersections might be changed into roundabouts to improve traffic flow.
    - The research team has experienced the challenges that roundabouts pose for AV operation, which seem to arise from the AVs' difficulty in finding appropriate gaps.
    - The impact of AV operation on roundabout design also depends on other factors, such as geometric design, standards, and traffic distribution. This indicates an essential need for further investigation.
- Two lane highways with shared turning middle lane
    - Three-lane roadways (with a shared turning lane in the middle) pose the most challenges in AVs' operation and experience the highest rate of safety-critical events compared to other lane configurations.
    - Following the 3-lane configuration, 4-lane, 2-lane, and 6-lane roads are ranked in descending order as the most challenging lane configurations.

    - Regarding lane markings, road sections with no clear markings exhibit higher rates of soft stops and circumventions; road sections with clear markings experience higher rates of E-stops.

Turning lanes and pockets

- The presence of turning lanes poses difficulties for AVs' operation.
- Left turn lanes and left turn movements exhibit the highest rate of triggered events.
- Notably, soft stops increase with left turn movements, while right turn lanes show a higher rate for E-stops and safety-critical events.

Emergency Stop Areas

- Emergency stop areas play a crucial role in ensuring the safe operation of AVs, particularly during disengagements.
- It is essential to document the locations of emergency stop areas to facilitate seamless navigation for AVs.
- Parking lots may be converted into emergency stop areas.
- Further research is needed regarding the possibility, frequency, and design standards for emergency stop areas in various scenarios, especially as AV numbers increase.
- Bridges
- Some authors suggest that the design of current bridges should undergo changes to account for the effect of platoons. In addition, they mention restricting the space between trucks as a potential solution to mitigate the platoon effect.
- The research team is of the opinion that there is no immediate need to change bridge designs, as the deployment of AV truck platoons is not currently considered viable. However, there might be a need to consider the weight of AVs/EVs alongside traditional factors related to truck weight and impact.

Charging stations

- Charging stations play a pivotal role in ensuring the effective operation of AVs by addressing battery-usage challenges that may lead to disengagements. Constructing charging stations near the operation site and implementing charging roads are among the potential solutions to tackle these challenges.
- When multiple shuttle brands operate in the same location, finding a universal solution for both short and long-term charging may be challenging.

Parking Lots

- The increased number of AVs reduces the need for parking lots due to the flexibility of AVs and the emergence of autonomous valet parking systems.
- There is a need to improve the parking lot infrastructure to solve navigation problems, especially in underground parking lots.

- It is advisable to allocate spaces near AV stations for bikes or cars to facilitate trip connections.

Overall Quality of Maintenance

- Effective operation of AVs relies critically on maintenance procedures, which should be adapted to varying seasonal demands. Neglecting these procedures may result in frequent disengagement of autonomy.
- Regularly checking road marking brightness and road sign clarity is crucial, as these factors significantly impact AV operation.
- Cleaning and maintaining AVs require special procedures owing to the presence of numerous sensitive sensors and hardware.

3.4 Public Acceptance of Low-Speed Autonomous Vehicles (LSAV)

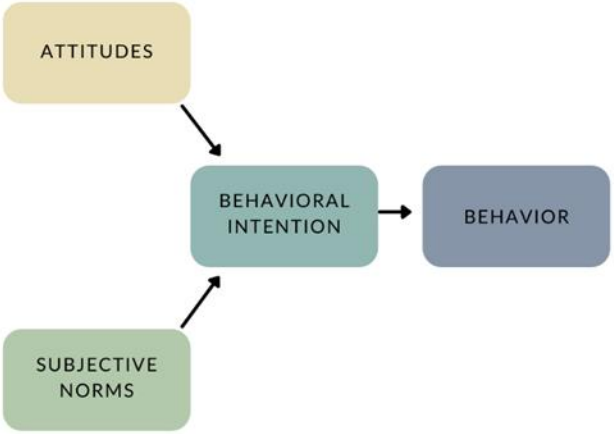
This section discusses the critical aspects of public acceptance of LSAVs. It explores various methods for assessing public acceptance, identifies key contributors to acceptance, reviews insights from AV pilot projects, and examines acceptance among individuals with special needs. Understanding these factors is essential for addressing public concerns regarding adoption of LSAV technology.

3.4.1 Methods for Assessing Public Acceptance of LSAVs

The assessment of user acceptance of technology is a pivotal aspect of understanding the potential success and integration of technological innovations in various contexts. Employing a range of methodologies, researchers seek to gauge how users perceive, adopt, and utilize new technologies. These methods typically encompass quantitative approaches like surveys and questionnaires, sometimes grounded in established theoretical frameworks. By adapting these methodologies to the specific context of LSAV, researchers can gain insights into the factors that will most significantly impact the acceptance and adoption of these vehicles among different user groups.

The Theory of Reasoned Action (TRA), introduced by Ajzen and Fishbein in 1967, is the first theoretical framework that aims to explain the relationship between attitudes and behaviors within human actions. TRA primarily aims to comprehend voluntary behavior in individuals by exploring the fundamental motivation behind an action. According to this model, the key determinant of whether a person will engage in a particular behavior is their intention to do so (behavioral intention). This intention is influenced by the surrounding social norms (normative component) and human attitudes. The behavior, shaped by the behavioral intention, will then lead to a desired outcome. TRA emphasizes that stronger intentions typically result in greater efforts to execute the behavior, thereby enhancing the probability of the behavior being actualized. Figure 3-12 illustrates the basic structure of the TRA.

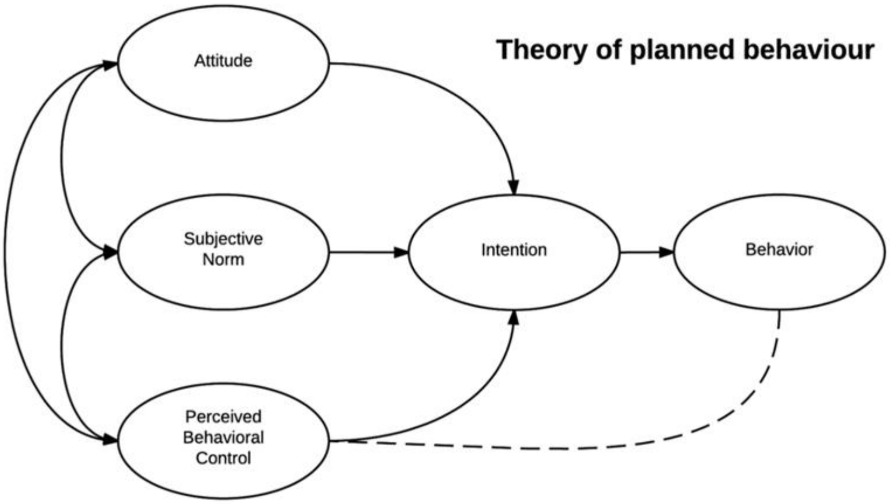
Figure 3-12. Theory of reasoned action



Source: Adapted from Ajzen & Fishbein, 1967

Ajzen (1985) extended TRA to the theory of planned behavior (TPB). Ajzen introduced the concept of perceived behavioral control that was absent in TRA. The TPB has found applications across numerous fields exploring the connections between beliefs, attitudes, behavioral intentions, and actual behaviors in diverse settings. Figure 3-13 presents the main structure of TPB. The TRA and the TPB are particularly effective in explaining the determinants of behavior primarily under conditions where there is significant motivation and ample opportunity for information processing.

Figure 3-13. Theory of planned behavior



Source: Adapted form Ajzen, 1985

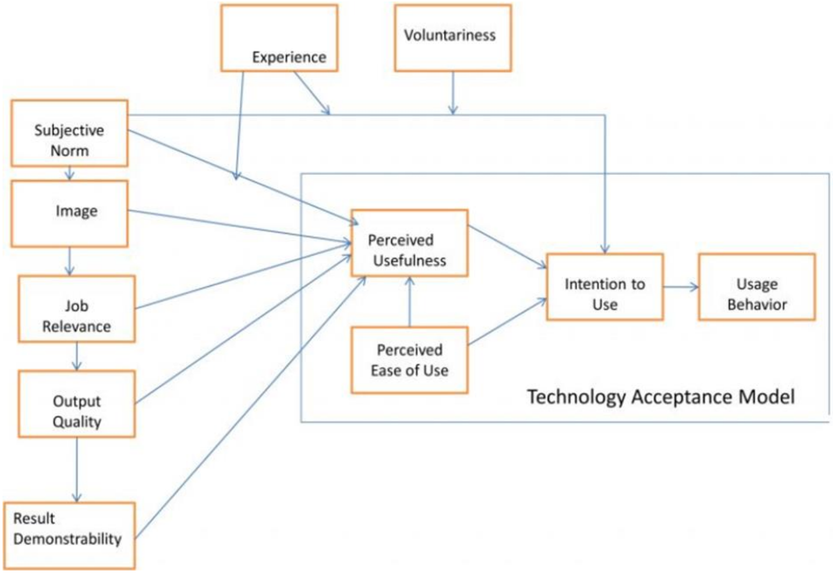
The Technology Acceptance Model (TAM) is one of the most prominent frameworks for understanding user acceptance and use of technology, as highlighted by Davis (1989). TAM serves as a refinement of the TRA, focusing on two critical factors for technology acceptance: perceived ease of use and perceived usefulness. This model simplifies the attitude measures in TRA by concentrating on these two aspects.

1. Perceived Usefulness (PU): It refers to the degree to which a person believes that using a particular system presents advantages compared to other choices. In the context of LSAV, this might involve beliefs about the efficiency, safety, and convenience of using AVs.
2. Perceived Ease of Use (PEOU): This is the degree to which a person believes that using a system would be free of effort. For LSAV, it refers to how user-friendly, intuitive, and easy to interact with these vehicles are perceived to be.

TAM has been extensively applied in exploring the acceptance of autonomous driving, as evidenced by studies conducted over the years, including Choi & Ji (2015), Panagiotopoulos & Dimitrakopoulos (2018), Lee et al. (2019), and Wu et al. (2019). According to King & He (2006) and Venkatesh (2000) TAM explains around 40% of the variance in behavior-related intentions and actual behavior.

However, primarily focusing on the determinants of perceived ease-of-use, the original TAM model did not comprehensively address the determinants of perceived usefulness. Venkatesh & Davis (2000) presented the second version of TAM (TAM2), including an examination of perceived usefulness and usage intentions. Specifically, TAM2 introduces additional constructs that encompass both social influence processes—such as subjective norm, voluntariness, and image—and cognitive instrumental processes, including job relevance, output quality, result demonstrability, and perceived ease of use. TAM2 can explain 60% of the variance in perceived usefulness and between 37% and 52% of the variance in usage intention (Venkatesh & Davis, 2000). Figure 3-14 illustrates a graphic overview of the original and the expanded model.

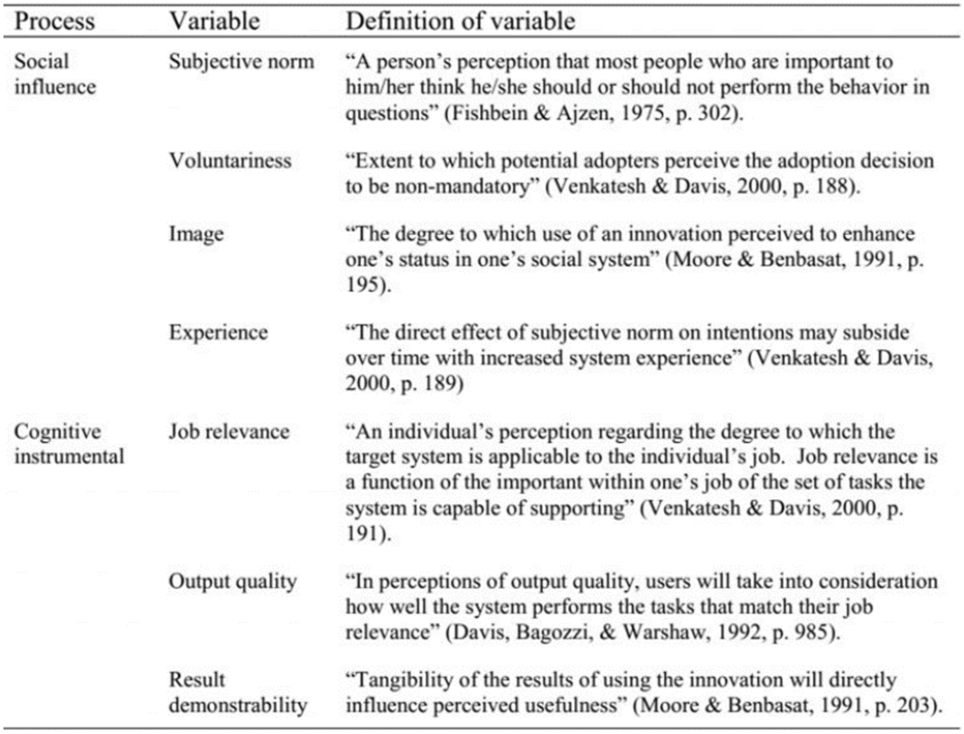
Figure 3-14. Technology acceptance model and technology acceptance model 2



Source: Adapted from Venkatesh & Davis, 2000

Table 3-9 represents the significant determinants of TAM2.

Table 3-9. Technology acceptance model 2 determinants



Process	Variable	Definition of variable
Social influence	Subjective norm	"A person's perception that most people who are important to him/her think he/she should or should not perform the behavior in questions" (Fishbein & Ajzen, 1975, p. 302).
	Voluntariness	"Extent to which potential adopters perceive the adoption decision to be non-mandatory" (Venkatesh & Davis, 2000, p. 188).
	Image	"The degree to which use of an innovation perceived to enhance one's status in one's social system" (Moore & Benbasat, 1991, p. 195).
	Experience	"The direct effect of subjective norm on intentions may subside over time with increased system experience" (Venkatesh & Davis, 2000, p. 189)
Cognitive instrumental	Job relevance	"An individual's perception regarding the degree to which the target system is applicable to the individual's job. Job relevance is a function of the important within one's job of the set of tasks the system is capable of supporting" (Venkatesh & Davis, 2000, p. 191).
	Output quality	"In perceptions of output quality, users will take into consideration how well the system performs the tasks that match their job relevance" (Davis, Bagozzi, & Warshaw, 1992, p. 985).
	Result demonstrability	"Tangibility of the results of using the innovation will directly influence perceived usefulness" (Moore & Benbasat, 1991, p. 203).

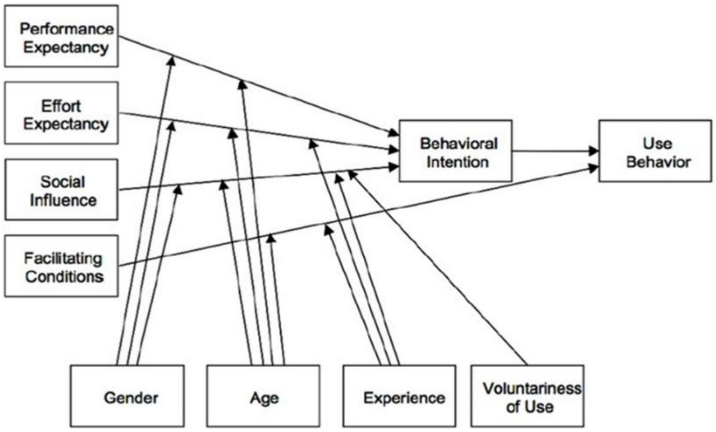
Source: Adapted from Venkatesh & Davis, 2000

One of the most important criticisms of the TAM model and its extensions is that it lacks critical factors that can influence technology acceptance. Several studies have highlighted the need for technology acceptance research to incorporate elements from the Theory of Planned Behavior, particularly the attitude construct (Yang & Yoo, 2004; Benbasat & Barki, 2007; Bagozzi, 2007).

Lastly, numerous researchers have expanded upon the original TAM model to integrate additional factors that significantly influence technology adoption and use. Notably, trust and perceived risk have been identified as critical extensions to the TAM framework. These extensions recognize that users' trust in technology and their perceptions of potential risks associated with technology use are vital determinants of technology acceptance. The importance of these additions is highlighted in studies such as Zhang et al. (2019), and Deng & Guo (2022).

The Unified Theory of Acceptance and Use of Technology (UTAUT), developed by Venkatesh et al. (2003), is a comprehensive model that integrates elements from eight previous models, including the TRA, TAM, Motivational Model, TPB, a combined TPB/TAM model, Model of Personal Computer Use, Diffusion of Innovations Theory, and Social Cognitive Theory. UTAUT identifies four primary constructs that influence user intentions and behaviors: performance expectancy, effort expectancy, social influence, and facilitating conditions. While the first three constructs predominantly determine the intention to use a system, the fourth directly impacts user behavior. The theory also recognizes the moderating effects of user characteristics such as gender, age, experience, and voluntariness of use on these relationships. According to Venkatesh et al. (2003), UTAUT offers a better predictive power compared to previous models accounting for 70% of the variance in use intention. Madigan et al. (2017) applied the UTAUT to study how the public perceives AV at SAE level 4 within road transport systems. Following a similar theoretical approach, Kaur & Rampersad (2018) explored the main factors influencing the adoption of AV as a service for public transit in restricted areas. Figure 3-15 presents the model structure of the UTAUT.

Figure 3-15. Unified theory of acceptance and use of technology



Source: Adapted from Venkatesh et al., 2003

Bagozzi, (2007) offered a critical perspective on UTAUT, acknowledging its well-intentioned and thoughtful nature, yet he pointed out its complexity with 41 variables to predict intentions and at least 8 for predicting behavior. He argued that this complexity contributed to a state of confusion in technology adoption research. Van Raaij & Schepers, (2008) also critiqued UTAUT, noting its lack of parsimony compared to earlier models like TAM and TAM2. They highlighted that its high explanatory power (high R2 value) is contingent upon the moderation of key relationships with numerous variables. Additionally, they questioned the methodology of grouping and labelling, pointing out that it combines a range of different items to represent single psychological constructs. Table 3-10 summarizes the basic features, advantages and disadvantages of the theoretical frameworks presented.

Table 3-10. Summary of the theoretical frameworks for measuring public acceptance

Model	***Key Features***	***Advantages***	***Disadvantages***
TRA	Focuses on the relationship between attitudes and behaviors, with intention as the key determinant of behavior.	Simplifies the understanding of behavioral intention and its impact on behavior.	May not account for other factors like perceived behavioral control.
TPB	Extends TRA by adding perceived behavioral control; focuses on the relationship between intention and behavior.	Incorporates an additional factor of perceived behavioral control, offering a more comprehensive understanding of behavior.	Can be complex due to the addition of perceived behavioral control.
TAM	Concentrates on perceived ease of use and perceived usefulness as the key determinants of technology acceptance.	Provides a focused approach to understanding technology acceptance, emphasizing ease of use and usefulness.	Originally limited in scope, focusing mainly on ease of use and usefulness.
TAM2	Expands TAM by including social influence processes (subjective norm, voluntariness, image) and cognitive instrumental processes (job relevance, output quality, result demonstrability).	Addresses additional factors like social influence and cognitive processes, enhancing the explanatory power of TAM.	Potentially complex due to the integration of numerous constructs.
UTAUT	Integrates constructs from multiple models; identifies four key constructs affecting usage intentions and behavior: performance expectancy, effort expectancy, social influence, and facilitating conditions.	Offers a comprehensive view by combining elements from various models, covering a wide range of factors influencing technology acceptance.	Criticized for its complexity and the method of grouping and labelling constructs; may lack parsimony.

For the study of public acceptance towards a new technology, quantitative approaches are crucial for systematically measuring and analyzing attitudes and behaviors. Among these methods, two popular approaches stand out: the Likert Scale Approach and the Dichotomous Approach.

The Likert Scale Approach involves presenting respondents with a series of statements, allowing them to express their level of agreement or disagreement on a five or seven-point scale, typically ranging from 'strongly disagree' to 'strongly agree'. This method is advantageous due to its ability to capture a nuanced understanding of attitudes, ease of administration and statistical analysis, and its capacity for facilitating comparisons across diverse groups or time periods. However, it does have drawbacks, such as the potential for central tendency bias, where respondents might overuse the neutral option, and the possibility that it may not fully capture the complexity of certain attitudes, like ambivalence. This method has been a popular choice in various studies related to AV, including those conducted by Miller et al. (2022), Othman (2021b) and Sitinjak et al. (2024). It has been also used in several pilot project reports to evaluate the public acceptance of LSAVs (University of Florida Lake Nona Report).

On the other hand, the Dichotomous Approach is more straightforward, asking respondents to simply answer 'yes' or 'no' to statements or whether they would be willing to use the new technology. This approach’s simplicity can lead to higher response rates and makes it easy to analyze data statistically. However, it lacks the nuanced data collection of the Likert scale, potentially reducing the richness of the data. It also does not allow respondents to express uncertainty or neutrality, which can be crucial in understanding complex attitudes. This binary response format has been demonstrated in many studies like those conducted by Barbour et al. (2019), Wang et al. (2020).

Table 3-11 presents a summary of the key features, advantages, and disadvantages of the two quantitative approaches commonly used to evaluate public acceptance of new technology.

Table 3-11. Quantitative approaches for measuring public acceptance of new technology

	Key Features	***Advantages***	***Disadvantages***
Likert Scale Approach	Respondents express their level of agreement or disagreement on a five or seven-point scale, typically from 'strongly disagree' to 'strongly agree'.	Captures nuanced understanding of attitudes, easy to administer and analyze, facilitates comparisons across groups/time periods.	Potential for central tendency bias, may not capture complexity of some attitudes, influenced by question phrasing.
Dichotomous Approach	Respondents answer simply 'yes' or 'no' to statements or questions.	Simple and straightforward, leading to higher response rates, easy to analyze statistically.	Lacks nuanced data collection, does not allow expression of uncertainty or neutrality.

The following point summarizes the main findings regarding the methods for assessing public acceptance of LSAVs**:**

- Assessing user acceptance of technology, particularly through surveys and questionnaires grounded in theoretical frameworks, is crucial for understanding the integration and success of innovations like LSAVs.
- Theoretical frameworks such as the TRA and TPB provide a foundation for understanding the link between attitudes, behaviors, and the role of perceived behavioral control.
- Extensions like the TAM and TAM2 further refine this understanding by emphasizing factors like ease of use, usefulness, social influence, and cognitive processes, though they face criticism for overlooking critical aspects like attitude, trust, and perceived risk.
- The UTAUT synthesizes elements from eight different models, concentrating on performance expectancy, effort expectancy, social influence, and facilitating conditions, but has been criticized for its complexity and lack of straightforwardness.
- Quantitative approaches to assessing technology acceptance include the Likert Scale, providing detailed insights but prone to central tendency bias, and the Dichotomous Approach, which simplifies data with 'yes' or 'no' answers but offers less depth in analysis.

3.4.2 Contributors to Public Acceptance

Among the various factors that influence public acceptance, one of the most important aspects to explore is the people’s interactions with LSAVs.

Empirical studies have often observed a positive shift in people’s “intention to use” after experiencing a ride with them. Particularly, the findings from the survey conducted during the AAA Free Self-Driving Shuttle Pilot Program revealed that 30% of the participants had a more favorable view of automated technology after they rode on the shuttles (Autonomous Vehicle Feasibility Study Final Report). Chee et al. (2021) reported that, in the long term, ride quality and comfort are the key factors that keep people using these services.

The Gainesville AS pilot deployment highlights a significant upswing in riders' comfort, relaxation, trust, and confidence levels after riding the AS (The Gainesville AS Report). Moreover, the before-after survey reveals a notable increase in the proportion of respondents who perceived that the AS provides a smoother ride than a regular bus, rising from 36.75% to 76.92%. For this reason, in many pilot programs, route locations were strategically chosen to generate maximum public attention. For instance, the MnDOT Autonomous Bus Pilot Project in Minnesota operated the shuttle during a Superbowl event, recognizing the influence of such exposure on public acceptance (MnDOT Autonomous Bus Pilot Project Report). Similarly, CityMobil2 demonstration in the city of Vantaa coincided with a housing fair, effectively shuttling attendees between the fair and a rail station (Final Report Summary -CityMobile2).

Finally, Jiang et al. (2022a) confirm the notion that public awareness plays a vital role in the public acceptance of LSAVs by reporting that individuals residing in the pilot cities demonstrated a heightened level of awareness and held a more favorable perception of self-driving shuttle programs in contrast to their counterparts in the non-pilot control cities.

Direct interaction with LSAVs significantly shapes public perception and familiarity, with pilot programs in various cities demonstrating that firsthand experiences, like rides in ASs, lead to increased comfort, trust, and a positive shift in the intention to use these vehicles.

3.4.3 Assessment of Public Acceptance from AV Pilot Projects

Lake Nona's Case Study offers valuable insights into the "perceived usefulness" of autonomous mobility. A noteworthy observation is the divergence in opinions between riders and non-riders regarding the convenience of the AV shuttle for navigating Lake Nona. Riders tended to perceive the shuttle as a convenient mode of transportation, while non-riders held the opposite view. This disparity can be attributed to a selection bias, where individuals who actively use a service are more likely to acknowledge its usefulness, possibly due to their firsthand experience. Another key finding from the report is the consensus among both riders and non-riders that increasing the operating speed of AV shuttles and expanding the service area coverage could serve as motivating factors for greater adoption (AV-Based Microtransit Service: A Case Study in Lake Nona). This suggests that enhancing the practicality and accessibility of autonomous mobility services can contribute to their perceived usefulness and, subsequently, their acceptance among the broader population.

The Gainesville AS report also provides insightful information into how different user groups perceive the shuttle's impact on various aspects of their daily experiences. For bus riders, the introduction of the AS led to a notably positive shift in their perceptions. They reported a smoother ride compared to regular buses, found the service to be more reliable, and believed that the shuttle was safer, both in terms of collisions with other vehicles and interactions with pedestrians and bicyclists. Pedestrians and bicyclists similarly felt that the shuttle was safer and more comfortable to be around when compared to regular buses (The Gainesville AS Report). Lastly, drivers expressed their belief that the shuttle is a safer option than a regular bus and poses a lower risk of colliding with their vehicle (Lee et al., 2019).

In the Yellowstone National Park Case Study, respondents strongly agreed with statements about their positive experience with the AV shuttle (Automation in Our Parks: Automated Shuttle Pilots at Yellowstone National Park and Wright Brothers National Memorial). They felt that the shuttle offered them reasonable travel times and safety during the COVID-19 pandemic. This positive feedback indicates that respondents found AVs useful in terms of providing a convenient and safe mode of transportation.

Additionally, the Campus Automated Shuttle Service Deployment Initiative Report reveals that most respondents saw potential in ASs replacing some of their walk trips on a large campus. This suggests that AVs are perceived as a useful solution for addressing transportation needs within a campus environment, potentially saving time and effort for students and staff (Campus Automated Shuttle Service Deployment Initiative Report).

Similarly, the Little Roady pilot program also demonstrated that smaller AVs were perceived as a first/last mile solution, particularly for older residents. Respondents considered them more energy-efficient and convenient for certain routes compared to larger transit options. This indicates that perceived usefulness is influenced by the specific context and demographic factors, such as age and route suitability (Little Roady Pilot Program Report). However, Jingyi Xiao's research introduced a critical perspective by noting variations in perceived usefulness based on household characteristics. This underscores the importance of recognizing that different groups may perceive the usefulness of AVs differently, especially regarding aspects such as work-related and child transportation, and highlights the need for a nuanced approach to promoting and adopting autonomous mobility solutions (Xiao & Goulias K, 2022). Table 3-12 summarizes the main findings regarding perceived usefulness.

Table 3-12. Main findings regarding perceived usefulness of AV shuttle

Pilot Study	**Key Findings**
Lake Nona	Riders find AV shuttles convenient, non-riders disagree. Increasing shuttle speed and coverage could motivate wider adoption.
Gainesville	Positive shift in perceptions among bus riders, pedestrians, and drivers about AV shuttle safety and reliability.
Yellowstone National Park	Positive experiences with AV shuttle during COVID-19.
Campus Shuttle	Potential for AVs to replace walk trips on campus.
Little Roady	AVs seen as a first/last mile solution, especially for older residents.

The reports from both the Lake Nona area and Gainesville AS pilot users reflect a generally positive perception of AV shuttle technology's ease of use. In Lake Nona, respondents displayed confidence in utilizing the AV shuttle, possibly due to their high education levels and technological competence (AV-Based Microtransit Service: A Case Study in Lake Nona). Similarly, in Gainesville, bus riders, pedestrians, and bicyclists conveyed positive feedback about ease of use, although drivers expressed frustration primarily due to the shuttle's slow speed (Gainesville AS report).

Ensuring a comfortable and enjoyable in-vehicle experience is crucial for increasing adoption, as evidenced by studies highlighting factors such as on-board comfort, spaciousness, and seating orientation influencing AV public transit acceptance (Paddeu et al., 2020)

To guarantee the future success and ease of use of shuttle services, the Campus Automated Shuttle report recommends implementing a system similar to the existing shuttle services. This system should include features like clear schedules and real-time tracking of the shuttle's path and location, enhancing convenience for students, staff, and faculty navigating the campus environment (Campus Automated Shuttle Service Deployment Initiative Report).

The Roady Shuttle Report underscores the significance of shuttle service frequency in user satisfaction (Roady Shuttle Report). Participants highly favored a 15-minute frequency compared to the less frequent schedules of many public buses. This preference emphasizes the importance of offering more frequent shuttle services to meet user expectations. Additionally, participants stressed the need for improved trip planning applications, providing real-time information on wait times and shuttle frequency. The absence of such information caused inconvenience when users failed to account for longer wait times during periods of low service frequency. Lastly, users expressed a desire for extended operating hours, especially during weekends and late-night trips, to accommodate returning train commuters and cater to nightlife activities.

In contrast, Rahim et al. (2023) concluded that perceived ease of use did not hold statistical significance. This outcome is attributed to the principle that variations in question design can yield differing results. For example, in the Lake Nona study, researchers assessed participants' perceived ease of use of an AV shuttle with the question, "If I want to use the AV shuttle, I think it will be easy for me (Even if I haven’t used it before)." Conversely, Rahim et al. (2023), the perceived ease of use was evaluated differently, with the question focusing on the necessity of having a steward on board: "I do not feel a steward on board is important for information." These distinct approaches to measuring perceived ease of use in the context of AS indicate the variability in research methodologies and highlight how different aspects are emphasized depending on the study's specific focus.

Table 3-13 presents a summary of the main findings regarding perceived ease of use.

Table 3-13. Main findings regarding perceived ease of use

Pilot Study	**Ease of Use Findings**
Lake Nona and Gainesville AS Report	Positive perception of AV shuttle's ease of use.
Campus Shuttle	Comfort and in-vehicle experience crucial for adoption. Recommendations for clear schedules and real-time tracking.
Roady Shuttle	Preference for frequent shuttle service and improved trip planning apps.
Rahim et al. (2023)	Perceived ease of use is not statistical important in their analysis.

A central aspect of public acceptance is the challenge of trust and safety in AV technology. Various studies have delved into these concerns, highlighting the criticality of safety and the public's trust in these machine-driven systems. The findings are presented in Table 3-14.

Table 3-14. Public perception and safety concerns in AV technologies

Year	Study (Authors)	Main Concerns/Findings	Percentage or Number of Respondents
2013	Jardim et al.	Safety was the most critical concern; cost and liability also important	Prioritized safety: 82%
2014	Schoettle & Sivak (US, UK, Australia)	AV safety, especially in adverse weather	High concerns: 92%
2015	Kyriakidis et al.	Security, legal aspects, and safety	5000
2016	Piao et al. (La Rochelle, France)	Safety is a key factor influencing public attitudes towards AV.	425 selected out of 500
2017	König & Neumayr	Safety concerns	489
2018	Greaves et al. (Australia)	AV system safety	High levels of concern: 68%
2016	Zmud et al. (Austin, US)	Lack of trust in technology and concerns about system safety.	Lack of trust: 41% System's safety concerns: 24%
2016	Bansal et al. (Austin, US)	Reliability of the equipment and equipment failure were top concerns	347
2022	Goldbach et al.	Impact of supervision level on willingness to use automated buses; concerns about vehicle speed.	Willingness decreased from 59% to 37%, and unwillingness increased from 14% to 42% as supervision decreased.

The studies conducted across different regions consistently reveal that users of ASs have specific expectations regarding the cost of the service. Users generally exhibit a reluctance to pay significantly more for SAM compared to the cost of existing transportation alternatives. Respondents in various studies, both in the United States and Europe, have expressed a preference for fares that are comparable to conventional public transit. Bansal et al. (2016) reports that a cost of USD 1 per mile (less than the corresponding Uber or Lyft cost) can lead around 41% of the respondents to use the shuttle service at least once per week. However, another study indicates that the reluctance to adopt SAM becomes evident when users are asked to pay significantly higher fares, as shown by the declining modal share when electric LSAV fares increased from USD 0.75 to USD 1.00 per mile, dropping from 39% to 14% (Zmud et al., 2016).

In the Lake Nona report, cost received the lowest score using a 1-5 Likert scale. An estimation of Move Nona's potential as a long-term public transit option, compared to the city bus system, revealed that AVs had a much higher cost per vehicle mile travelled, indicating that the price of the AV shuttle may be too high (AV-Based Microtransit Service: A Case Study in Lake Nona). This raises questions about how long AVs can continue to attract investors and riders when the initial curiosity diminishes.

The points below present the key insights on public acceptance from assessments of pilot projects.

- The perceived usefulness of autonomous mobility, as illustrated in pilot projects reveals that while riders generally find AV shuttles convenient, factors like shuttle speed, coverage, safety, and demographic variations such as age significantly impact overall public perception and potential adoption.
- In the context of perceived ease of use, studies from Lake Nona, Gainesville, and the Roady Shuttle Report highlight a positive perception of AV shuttles' user-friendliness, emphasizing the importance of comfort, in-vehicle experience, clear scheduling, real-time tracking, frequent service, and enhanced trip planning applications for successful adoption.
- The perception of risk and trust in AV technology is fundamentally shaped by safety concerns, where users' trust levels and the extent of system supervision significantly affect their willingness to adopt and use AVs and automated buses.
- Users are reluctant to pay more for SAMs compared to regular transit fare, suggesting that the high cost of AV shuttles might affect their future popularity and use.

3.4.4 Public Acceptance for People with Special Needs

Understanding the factors that influence the attitudes of individuals with disabilities towards AVs is of paramount importance. Bennett et al. (2019; 2020) indicate that in their research several key factors emerged as significant determinants of attitudes among people with disabilities regarding AVs. First, the level of interest individuals held in new technology played a pivotal role. Those with a higher interest in technology tended to exhibit more positive attitudes toward AVs. Conversely, anxiety levels related to AV technology had a notable impact, with higher anxiety levels associated with more negative attitudes. Additionally, the severity and intensity of an individual's disability were found to shape their attitudes towards AVs. Those with more intense disabilities often had distinct perceptions and requirements regarding AV technology. Prior knowledge of AV technology also proved influential, as participants with more knowledge tended to hold more positive attitudes. The degree to which individuals felt they had control over their interactions with AVs, known as "Locus of Control," played a role in shaping attitudes. Lastly, an individual's proactive approach toward technology and mobility options, termed "Action Orientation," influenced their attitudes.

Hwang & Kim (2023) and Hwang et al. (2021; 2020) explored the perceptions of people with disabilities towards AVs and indicated that participants expressed anxiety about AVs due to the absence of human operators, a concern particularly critical for individuals with disabilities who often felt a sense of security with human intervention. Existing issues with public transit and built environments motivated people with disabilities to explore AV technology as a potential solution to address their mobility challenges. Some participants also voiced concerns that AV shuttles might become less disability-accessible in crowded conditions, underscoring the importance of maintaining accessibility features.

The final report of the STRIDE A5 Project corroborate the findings of previous studies and indicates that individuals with disabilities expressed a desire for an option for human intervention in AVs, as they felt a sense of distrust and reduced safety without this option (STRIDE A5 Project). The project report also reveals that exposure to SAMs has been shown to have a positive impact on the perceptions and attitudes of individuals with disabilities towards AVs. Exposure to LSAV has led to increased intentions to use this technology, greater acceptance of this emerging mode of transportation, and a heightened likelihood of eventual adoption (STRIDE A5 Project). These results align with those of previous studies, underscoring the positive impact of exposure to LSAV on user attitudes and behaviors (Duncan et al., 2015; Pakusch & Bossauer, 2017). Lastly, several strategies have been proposed to address the anxieties that may arise during the early stages of AV transportation services effectively. These strategies encompass the implementation of security equipment within AVs, the launch of comprehensive public information campaigns, the organization of outreach and education initiatives, especially for older adults, active involvement of diverse user groups in pilot projects, and the establishment of reliable channels for disseminating information (Chen & Kockelman, 2016; Rahman et al., 2019; Goldbach et al., 2022; Greaves et al., 2018).

The following were the findings from this section:

- Individuals with disabilities express a preference for human intervention due to feelings of distrust and reduced safety in the absence of this option, a concern distinct from other user groups.
- Exposure to LSAVs like ASs has a positive impact on the perceptions and attitudes of individuals with disabilities towards AVs, leading to increased intentions to use AV technology and greater acceptance of this emerging mode of transportation.

3.5 Regulations

Effective regulations are essential for the safe and efficient integration of AV into the existing transportation system. The government, both at the federal level and in different states, has been creating rules to guide how and where AV can be deployed. In order to bring consistency and achieve a set of regulations at both the federal and state levels, in 2016 the National Highway Traffic Safety Administration (NHTSA) specified the jurisdiction and responsibilities for each entity. At the federal level, NHTSA is mainly responsible for safety aspects such as developing and implementing safety standards, ensuring compliance with Federal Motor Vehicle Safety Standard (FMVSS) for new vehicles, addressing non-compliance and vehicle defects, enhancing public awareness of safety issues, and providing guidance frameworks for manufacturers. While states are mainly responsible for, "licensing (human) drivers and registering motor vehicles in their jurisdictions, enacting and enforcing traffic laws and regulations, conducting safety inspections, where States choose to do so, and regulating motor vehicle insurance and liability". Also, it emphasizes that in any conflict between state and federal regulations, NHTSA regulations should be prioritized and followed (U.S. Department of Transportation, 2016). This part of the literature review discusses the proposed regulations and considerations.

3.5.1 Overview of Federal Regulations

Based on the NHTSA federal automated vehicle policy, manufacturers or other entities are responsible to identify their products' level of automation. Therefore, they provide a framework to guide manufacturers in addressing the critical areas before testing or deploying AVs. In this context, gaining a certification to ensure capability of products with FMVSS is the first step that manufacturers should take. These standards generally include three sections: crash avoidance, crashworthiness, and post-crash standards (U.S. Department of Transportation, 2016). Initially, these standards had been drafted regardless of the AVs characteristics. However, in 2020, the U.S. Department of Transportation (U.S. DOT) published a document to make regulations more adaptable to AVs, covering crash avoidance and crashworthiness standards (National Highway Traffic Safety Administration, 2020).

NHTSA stated that these standards would not prevent manufacture making innovation in their products. NHTSA provides manufacturers with various alternatives to ensure product compliance, including the option to seek clarification through Interpretation Letters to understand the regulations better. If their products are found to be incompatible, manufacturers can also request temporary exemption letters (U.S. Department of Transportation, 2016). According to Columbus (2021), there is a lack of a clear, standardized timeline, which varies with route complexity and proximity to sensitive areas like schools. This challenge can lead to delays in project deployment. To mitigate this delay, they recommend submitting a preliminary testing route before the full route application to facilitate the implementation process and adhere to deployment schedules. Similarly, the deployment of the Gainesville AV Shuttle demonstrated the importance of such a strategy. The shuttle's operators worked closely with the UF team to gather and submit essential traffic and safety data for the test route to the NHTSA. This emphasizes the critical role of a strong stakeholder alliance, as its absence can make the implementation process more complex and time consuming.

According to a survey, that (Nair & Bhat, 2021) conducted to capture public opinion, there was a general consensus that while AVs are operating, there should be an operator ready to take control in case of any disengagement. Therefore, it suggests that regulators should not only emphasize safety aspects in their policy legislation but also develop plans to increase public awareness in order to alleviate safety concerns (Nair & Bhat, 2021). To improve public knowledge, since 2013, after AVs began operating on public roads, the California Department of Motor Vehicles has held several workshops, which are accessible through its website (California Department of Motor Vehicles, n.d.). Given the concern regarding whether the presence of operator safety is necessary or not, (U.S. Department of Transportation, 2016) states that for driving a vehicle with less than full autonomy (SAE Levels 3 and lower) a licensed drivers should be present to monitor the operation and take the control of the vehicle in the case of disengagements. While, for a fully automated vehicle (SAE levels 4 and 5) there is no need for licensed human drivers.

Liability and insurance are pivotal factors for the successful deployment of AVs. In this context, the NHTSA suggests that making AVs as safe as possible can serve as the first step to addressing liability concerns. Also, it states that in the event of accidents, it is the obligation of states to define liability policies. States should establish clear guidelines for apportioning liability among all the parties involved in an accident, including vehicle owners, operators, passengers, and manufacturers. Moreover, due to the complex liability scenarios with AVs, states could consider establishing higher minimum insurance requirements for AVs. This would not only ensure that victims are adequately compensated but also incentivize manufacturers to maintain high safety standards (U.S. Department of Transportation, 2016).

The Operational Design Domain (ODD) is another parameter that manufacturers or entities must clearly outline and record for each AV system they wish to test or deploy on public roads. SAE J3016 defines the ODD as “Operating conditions under which a given driving automation system, or feature thereof, is specifically designed to function, including, but not limited to, environmental, geographical, and time-of-day restrictions, and/or the requisite presence or absence of certain traffic or roadway characteristics.” (SAE On-Road Automated Driving (ORAD) Committee, 2016). Essentially, the ODD defines the operational scope within which the autonomous system can safely and efficiently navigate, taking into account various external factors that could impact its performance. To clarify the concept of the ODD with an example focusing on robotaxis and AV: robotaxis primarily operate in urban environments and their ODDs cover specific conditions such as dense traffic, pedestrian interactions, and urban infrastructure. In contrast, AV can have a broader range of ODDs that cover a wide variety of operational scenarios. As the level of autonomy in AVs increases, their ODDs expand, meaning these vehicles are designed to operate under a wider condition without limitations. In this context, NHTSA states that it is essential for manufacturers to establish a comprehensive process for evaluating, testing, and verifying the HAV system's performance within these specified domains (U.S. Department of Transportation, 2016).

Cybersecurity is another important concern that should be discussed in policy development. The NHTSA suggests following the related standards published by organizations such as the National Institute for Standards and Technology (NIST), NHTSA, SAE International, etc., as an effective approach to minimize the risk of cybersecurity attacks. Another vital factor is the implementation of cybersecurity-related data documentation in a way that ensures compliance with consumer privacy agreements and is also available upon request by the NHTSA. Moreover, all this information should be shared via the Auto-ISAC to promote collective learning and enhance the industry awareness (U.S. Department of Transportation, 2016). Additionally, the federal legislation proposed that all should identify all vulnerabilities in the system that could result in cybersecurity issues and implement strategies to prevent them. Training employees and identifying a central point of contact specifically for cybersecurity matters are other courses of action that should be taken (U.S. House of Representatives, 2020).

Filing the required regulation to improve the accessibility of AVs (both AV shuttles and all kinds of vehicles with autonomous systems) for disabled individuals is another crucial parameter. In this context, Fiol and Weng (2022) mentioned that the federal government can set new regulations and mandate specific designs in vehicles that provide for the needs of disabled individuals, such as wheelchair access, or the needs of deaf and blind people. The U.S. House of Representatives (2020) mentioned that in issuing exceptions, those factors that can facilitate usage by disabled individuals and improve accessibility should be considered. However, current regulations do not explicitly require AVs to be accessible for people with disabilities (Fiol & Weng, 2022).

The ethical implication is another factor that all entities should consider in making AV-related decisions. This means that each action should be taken after considering various outcomes to manage conflicts between safety, mobility, and legality (U.S. Department of Transportation, 2016). United Nations Economic Commission for Europe (UNECE) (2022) illustrates this matter with an example, stating that current traffic laws were designed for conventional vehicles, thereby questioning their applicability to AVs. In this regard, it might be more beneficial for automated driving systems (ADS) to dedicate computational resources to optimizing trajectories and interactions to prevent accidents or reduce their severity, instead of predicting potential victims in crash scenarios. In this scenario, giving preference to traffic operation over safety considerations represents an ethical concern that must be addressed.

3.5.2 Overview of State Regulations

As mentioned in the previous section, each U.S. state is responsible for drafting regulations related to traffic rules and complete the federal regulation using the proposed framework. For example, concerning ODD, the California Department of Transportation discusses the requirements in more detail compared to federal regulations. It specifies that manufacturers must clearly state the ODDs where their AVs are designed to operate and ensure these vehicles cannot operate in autonomous mode outside these designated areas. They are required to list any conditions, such as snow, fog, or construction zones, under which the vehicles cannot drive autonomously or explain how the vehicle will safely deactivate autonomous mode in such situations. Additionally, manufacturers must describe what actions the vehicle will take if it finds itself outside its ODD or encounters challenging conditions. These actions may include alerting the driver, slowing down safely, moving off the road, or stopping (California Department of Motor Vehicles, 2023).

As another example, considering the liability concern, the legal framework specifically addresses scenarios where a vehicle is transformed into an AV by a third-party company. Under this framework, if any injuries are caused by the equipment or modifications made during the autonomous conversion, the original manufacturer of the vehicle is not held legally responsible. Therefore, any defects or issues arising from the conversion process are the responsibility of the party performing the conversion. However, the original manufacturer remains accountable if the cause of the injury can be traced back to a defect that was present in the vehicle at the time of its original manufacture (Florida Department of Highway Safety and Motor Vehicles, 2023). In this context, Table 3-15 provides an overview of different state regulations for AVs.

To address the requirements for disabled individuals from a state regulation perspective, the U.S. House of Representatives (2020) noted that states are prohibited from discriminating against individuals with disabilities when issuing vehicle operator’s licenses for AVs. Furthermore, Fiol & Weng (2022) suggested designing pickup and drop-off curb points specifically to make AV usage easier for people with disabilities and proposed the issuance of subsidies or vouchers to assist them. Currently, state regulations, similar to federal regulations, have not incorporated these specific requirements (Fiol & Weng, 2022).

Table 3-15. Overview of states' regulations

State	Operational Design Domain	Liability and Insurance	Safety	Traffic Operation	Human Operator	Other
Nevada	Just the definition of ODD has been described.	Significant insurance. Limit manufacturers liability for unauthorized modifications.	Mandates reporting significant crashes within a specific timeframe. Protocols for manual takeover and system failures.	AVs must adhere to existing traffic laws.	Specifies conditions under which human intervention is necessary.	Adopting regulations related to operation, testing, certification, and licensing regarding AVs.
Florida	Just the definition of ODD has been described.	Mandates $5 million coverage for testing. Exempts original manufacturers from liability for defects from third-party conversions.	Safety protocols include system alerts for failures and achieving a minimal risk condition. Ensures federal safety standard compliance	Adherence to state laws required.	Not needed for full autonomy. For others, systems must alert operators to take control during failures.	Covers registration and testing protocols.
New York city	Ensuring vehicles operate safely within specific urban environments.	Requires an insurance policy covering personal liability and property damage.	Mandates rapid reporting of incidents to the Department. Certificate requirements for operator training and cyber security measures.	Strict adherence to traffic laws and safety protocols is required.	Requires a trained operator ready to take control during tests.	Covers permit application, fees, and conditions for testing and demonstration in NYC
California	The definition. Manufactures should specify vehicles' ODD.	Mandates $5 million insurance coverage. Focuses on manufacturer's responsibility and safety protocols.	Mandates reporting accidents within 10 days. Detailed training programs and safety plans for emergency situations.	Ensures compliance with traffic laws and safety standards.	Defines roles for test drivers and remote operators.	Covers permit application processes, testing conditions, and public road operation prohibitions. One of the most comprehensive regulations at the state level.

Table 3-15, continued

State	Operational Design Domain	Liability and Insurance	Safety	Traffic Operation	Human Operator	Other
Arizona	Just the definition of ODD has been described.	Must “meet all applicable title, registration, licensing, and insurance requirements”.	AVs must stop at accident scenes, and owners must report accidents and provide necessary information. Must ensure minimal risk conditions in system failure and comply with federal laws and standards.	Must comply with all traffic and motor vehicle safety laws.	Not required for fully AVs but must be capable of resuming control if needed.	Includes exemptions from certain equipment requirements, and provisions for law enforcement AVs interactions.
Texas	Nothing specified.	Specifies liability insurance requirements. Defines system owner as vehicle operator for legal purposes.	Requires adherence to existing accident reporting laws. Requires system compliance with federal standards and vehicle registration.	Must comply with state traffic laws.	Not required when the system is engaged.	Prohibits local regulation beyond state laws.
Michigan	Allows operation on any street or highway in Michigan, with specific conditions for monitoring and control.	Mandatory insurance requirements.	Emphasizes the ability to monitor and control the vehicle, ensuring it can achieve a minimal risk condition if control is lost.	AVs are allowed on public roads.	Allows for autonomous operation without a human operator, with provisions for monitoring and control.	Discusses the operation of platoons, highlighting regulations around vehicle interaction.

3.5.3 Summary

This section reviewed the regulations that have been proposed for AV deployment at both the federal and state levels. It was concluded that:

- Both the federal and states are responsible for drafting regulations for AV deployment. However, the federal government is mainly responsible for addressing safety concerns, while states are responsible for addressing traffic-related issues.
- NHTSA offers exemption letters for situations where manufacturers’ products are not compatible with some of the standards. However, it is a time-consuming process with lots of uncertainty, which can result in delays in project deployment.
- There are still some important gaps in regulations that should be addressed through collaboration between federal and state authorities, such as defining how related departments must respond to emergency situations or the infrastructure requirements for AV deployment.
- The lack of harmonization between federal and states regulations, especially among different states, can pose challenges in AV deployment. Each state has its own traffic regulations, which are distinctive from those of other states, making it difficult for manufacturers to ensure compatibility with all states’ regulations.
- There should be more specific regulations for cybersecurity issues; current regulations are mostly in the form of frameworks and merely suggestions. This level of uncertainty can pose challenges for manufacturers in AV deployment.
- Although addressing the needs of disabled individuals is an important concern in regulations (such as when issuing vehicle operator’s licenses or when designing pickup and drop-off curb stops), it has not been extensively discussed in either federal legislation or state laws.

3.6 AV Shuttle as a Service

This section discusses the integration of ASs as a service within existing transportation systems, highlighting the challenges they face and their potential as a last-mile solution. It examines the barriers to public transit accessibility, especially for people with disabilities, and explores the role of shared autonomous mobility in enhancing urban transportation networks. Understanding these aspects is crucial for optimizing the deployment and acceptance of AVs.

3.6.1 Challenges Faced by Existing Transportation Systems

Public transit systems are crucial for urban mobility, providing access to jobs, education, and services. However, research highlights significant gaps and inefficiencies within these systems, particularly accessibility challenges for individuals with disabilities, geographic disparities in transit coverage, and structural and infrastructural barriers impacting multimodal integration and safety of emerging micromobility solutions such as e-scooters.

The NHIS-D, part of the annual survey conducted by the Bureau of Transportation Statistics of the US Department of Transportation in 1994, provides valuable insights into the challenges faced by individuals with disabilities in accessing public transit[8]. According to the survey, 13% of respondents with a disability reported difficulties in using public transit, primarily in walking, followed by the need for assistance from another person. Furthermore, 90% of respondents who did not use specialized transportation options, such as special buses and services, reported no need or desire for such services. This finding suggests a disconnect between the services offered and the actual needs or preferences of individuals with disabilities, indicating that current public transit may not adequately meet the needs of this population. While a national-scale effort such as the NHIS-D has not been conducted in recent years to our knowledge, the findings from the 1994 survey are largely applicable to today's situations.

AVs have the potential to significantly enhance mobility for people with disabilities, particularly addressing the challenges in first and last mile connections that are crucial for accessing public transit. These segments are often fraught with barriers such as poor sidewalk conditions and inaccessible public spaces. AVs can provide door-to-door services, making travel much easier and more accessible for people with disabilities. These vehicles can be equipped with features such as automatic ramps and auditory systems for the visually impaired. The deployment of AVs requires the integration of universal design principles to ensure these technologies are accessible to all, promoting inclusivity and preventing the exclusion of people with disabilities from social participation. This comprehensive approach not only benefits those with specific needs but also improves the overall public transit system by making it more accessible and user-friendly (Nanchen et al., 2022).

Classen et al. (2023) emphasize the necessity for AV to be accessible to all users, including those with disabilities. This requires ensuring that the design of ASs adheres to ADA standards, advocating for universal design that accommodates individuals with various disabilities, including those related to mobility, sensory, and cognitive impairments. Additionally, Hwangbo et al. (2024) highlights the critical need for real-world testing and feedback from this group to refine and adapt the technology accordingly. Mason et al. (2024) also underscores the necessity for policy revisions to keep pace with technological advancements, ensuring that these innovations truly align with the evolving needs of the disabled community. Together, these approaches aim to bridge the gap between current AS capabilities and ADA compliance requirements, ensuring that these transportation solutions are truly inclusive and beneficial to all, particularly those with disabilities.

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[8] https://www.cdc.gov/nchs/nhis/nhis_disability.htm

Clark & Wang (2010) argue that transportation access is a multimodal challenge, emphasizing that while public transit is considered a key mode, public transit alone cannot fully address the issue of transportation access for everyone. A comprehensive set of shared-use mobility options is needed to satisfy the travel needs of people without vehicles. .

In the quest to enhance urban transportation and make it more accessible and efficient, different systems have been introduced. Among these solutions, paratransit, microtransit, micromobility, and bikeshare programs stand out as significant developments. Each system offers unique advantages and challenges, and together, they represent diverse approaches to improving public transit. Their effectiveness in addressing transportation needs, and the barriers they face in integration and adoption within urban environments, are discussed in the subsections below.

3.6.1.1 Paratransit

Despite being a critical component of public transit for people with disabilities, ADA paratransit services have limitations that reduce their effectiveness. These services often operate as a reservation-based system, requiring advance scheduling of up to 24 hours or more, which in turn severely limits the ability of users to make spontaneous or urgent trips (Murphy, 2016). This contrasts with the flexibility offered by standard public transit systems, where services are more frequent.

Additionally, the cost of providing paratransit services is very high compared to fixed-route bus services. A study by the Federal Transit Administration (FTA) reported that from 1999 to 2012, the number of annual ADA paratransit trips rose from 68 million to 106 million. During the same period, the cost per trip escalated from $14 to $33, marking a 138% increase. In comparison, the unit cost for fixed-route bus services went up by 82% (Golden et al., 2014).

For some users, especially low-income riders, the cost of ADA trips can be a significant barrier to transportation. This financial burden exacerbates transport poverty, where the combination of high costs and inadequate service provision leads to increased social exclusion and diminished well-being (Lucas 2012).

3.6.1.2 Micro-transit

Micro-transit is a form of demand-responsive transportation that offers flexible services tailored to individual travel needs, typically operating with dynamically routed vehicles. These services attempt to bridge the gap between traditional fixed-route public transit, aiming to provide more personalized and convenient travel options (Currie & Fournier, 2020).

On-demand micro-transit also face significant barriers to adoption in relation to accessibility and ease of use. According to a recent study analyzing the perspectives of paratransit users, a substantial portion of respondents identified key issues that hinder their transition to micro-transit options. Specifically, 15% of users cited a lack of spatial coverage, meaning the micro-transit services do not extend to all areas needed by the users, thereby limiting their utility.

Additionally, 13% of the respondents reported inadequate walking access to micro-transit pick-up locations, which poses a challenge for those who might find it difficult to reach designated spots due to mobility issues or unsafe pedestrian paths (Miah et al., 2020).

While providing door-to-door convenience and the appeal of on-demand travel, these services struggle to maintain financial and operational sustainability as ridership increases. For instance, despite their initial popularity, microtransit systems require substantial subsidies to operate, with cities like Los Angeles spending significantly more per microtransit trip compared to traditional bus services (Miah et al., 2020). Furthermore, the operational costs do not decrease proportionally with increased ridership, which contradicts the economies of scale that fixed-route services benefit from (TransitCenter, 2021).

3.6.1.3 Micromobility

Micromobility, which includes the use of lightweight vehicles such as e-scooters and e-bikes has rapidly emerged as a popular mode of transportation in urban environments, particularly in cities with an established bike culture[9]. These small-scale vehicles, characterized by their limited mass and design speed, are popular not only for individual use but are also increasingly being integrated with public transit systems. This integration aims to enhance urban mobility by providing effective solutions for the first and last mile of a commuter’s journey (Oeschger et al., 2020). However, just as public transit systems face barriers in serving all community members effectively, e-scooters face various obstacles that limit their potential to enhance urban mobility, including their integration with public transit. A significant challenge identified by Manning and Babb (2023) through their survey findings is the issue of first and last-mile connectivity, particularly in the context of e-scooter usage. The ability of e-scooters to seamlessly integrate into the urban transportation network is compromised by low-density urban forms and the lack of adequate and connected infrastructure. Their case study revealed that 42% of respondents identified low-density urban forms as a significant barrier to e-scooter efficiency, indicating that sprawling urban layouts with dispersed destinations make e-scooter use less viable and attractive compared to denser urban areas (Manning & Babb, 2023). Furthermore, 34% of respondents pointed to the inadequacy of connected infrastructure as a major inefficiency. This encompasses not only the physical infrastructure, such as dedicated lanes and parking spots, but also the integration with other modes of public transit. The lack of safe, dedicated lanes for e-scooters and clear regulations for their use on roads and sidewalks creates safety concerns and operational challenges, discouraging their use and limiting their potential as a reliable transportation option (Manning & Babb, 2023).

Kobayashi et al. (2019) and Sikka et al. (2019) have documented the significant rise in e-scooter usage and the corresponding increase in crashes involving these micromobility vehicles. This increase in accidents highlights a critical oversight in the rapid deployment of e-scooters — the

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[9] http://time.com/5659653/e-scooters-cycles-europe/

lack of adequate safety measures and regulations tailored to this new form of transportation. Additionally, Liao & Correia (2020) further the discussion by addressing the spatial challenges posed by e-scooters, particularly concerning the use of pedestrian lanes (this term is used in the paper) and sidewalks. E-scooters, often ridden at relatively high speeds compared to pedestrian traffic, can pose significant risks to walkers, including the potential for injuries. Moreover, the issue of e-scooters being parked on sidewalks presents another dimension of the challenge, obstructing pedestrian paths and contributing to urban clutter (Liao & Correia, 2022). This underscores a critical conflict in the allocation of urban space, where the infrastructure has not kept pace with the advent of micromobility solutions.

3.6.1.4 Bikeshare

Bikeshare programs have also emerged as a popular urban transport solution. Recent studies have explored the factors influencing the adoption and use of bikeshare systems, particularly highlighting the role of socio-economic and built environment variables. Franckle et al. (2020) conducted a comprehensive study focused on the use of bikeshare programs in Boston among lower-income populations. Their findings suggest that both frequent and infrequent users recognize the benefits of bikeshare services, such as convenience, access, health benefits, and economic advantages. However, the frequency of usage significantly alters the perception of these benefits. Regular users are more likely to appreciate these benefits compared to their less frequent counterparts. Conversely, barriers like helmet requirements, rental issues, and adverse weather conditions are more pronounced for occasional users.

Another research identifies key barriers to bikeshare use in an urban environment, categorized into three categories: predisposing (intrapersonal), reinforcing (interpersonal), and enabling (structural) factors. Key intrapersonal barriers include lack of awareness about the program, unfamiliarity with the technology of the bike sharing rental procedure, and physical limitations due to age or disability, which are somewhat mitigated by the availability of electric bikes. Interpersonally, having a family is a significant obstacle due to the adult-centric design of bikes and lack of child-carrying provisions. Structurally, the absence of dedicated bike lanes, unsafe traffic conditions, prohibitive costs, and restrictive policies (like the 45-minute check-out limit) are major impediments. Additionally, the physical heaviness of the bikes and limited availability of electric models pose further challenges, particularly during extreme weather conditions, hindering widespread adoption of bikeshare systems (Bateman et al., 2021).

3.6.2 Shared Autonomous Mobility on Demand as a First/Last Mile Solution

Shared Autonomous Mobility on Demand (AMoD), with AV shuttle or robotaxi being the operational model, has a great potential to serve as a first/last-mile solution in bridging the gap between major transit hubs and final destinations. AMoD systems employ SAVs that users can request on demand. These vehicles can pick up users from their current locations and transport them to nearby transit hubs or provide transport from these hubs to the users' final destinations.

They are designed to streamline the connection between individual travel needs and public transit systems (Huang et al., 2022). This section explores studies that have investigated the efficacy, optimization strategies, and impacts of AMoD systems in various urban contexts, illustrating the potential of AVs in enhancing the sustainability and efficiency of urban transportation networks.

Huang et al (2023) indicate that by offering more direct and efficient routing options and facilitating ridesharing, AMoD increases overall transit utilization, leading to higher ridership and the potential for more frequent transit services. Additionally, the article indicates that AMoD provides cost-effective transportation solutions by optimizing routes and integrating fares with existing public transit systems, ensuring competitive pricing and seamless travel experiences. Unlike traditional fixed-route services, AMoD can dynamically respond to fluctuations in rider demand throughout the day. This adaptability improves service during off-peak times and in less densely populated areas, maintaining efficient connectivity and encouraging broader use of public transit systems (Gurumurthy et al., 2020).

Other studies and demonstrations indicate that ASs can substantially improve the quality of public transit systems, especially in rural areas and low to medium-demand urban areas. For instance, full-scale demonstrations of autonomous mini-buses in Geneva, Lyon, Copenhagen, and Luxembourg have highlighted the feasibility of deploying such technology in varying cityscapes[10]. The municipality of Koppl in Austria views ASs as a viable solution for bridging the gaps left by infrequent bus services in village areas (Rehrl & Zankl, 2018), underscoring the potential for micro-transit systems to enhance connectivity. Meyer et al., (2017) mention the potential benefit of AVs in increasing accessibility and reducing travel times, particularly in well-connected exurban and rural municipalities, where congestion on arterial roads and highways during peak hours significantly degrades travel times. Bowling (2020) and Hsueh et al. (2021) emphasize the potential of ASs to increase the mobility of disabled passengers and improve first- and last-mile (F&LM) connectivity. However, issues such as low demand during off-peak hours can lead to reduced service frequency, which in turn decreases connectivity between stations and the system's overall efficiency.

However, despite the potential benefits, the operational expense of ASs has been identified as prohibitively high (Litman, 2018; Rehrl & Zankl , 2018), suggesting a significant barrier to the widespread adoption of ASs on public roads. This financial challenge highlights the need for sustainable funding models to fully realize the benefits of autonomous micro-transit systems.

Understanding user reactions to AMoD as a viable first/last-mile transportation option compared to other available modes is a critical factor in urban mobility planning. Wicki et al. (2018) conducted a quantitative assessment to understand the mode choice decisions among users, considering ASs, rental bikes, and walking as the primary alternatives. The study gauges the

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[10] https://h2020-avenue.eu/demonstrator-sites/

general attitude towards ASs and evaluates specific attributes such as waiting time, ticket availability, and the physical ability of respondents to walk or bike. The results of the study reveal some critical insights into the dynamics of mode choice among urban commuters:

- *AS Preference:* The preference for ASs decreases as travel time, waiting time, and costs increase. This finding underscores the sensitivity of AS mode choice to efficiency and economic factors.
- *Physical Ability and Mode Choice:* Individuals who are physically able to walk or ride bikes tend to prefer these options over ASs. This preference highlights the importance of personal capability and the intrinsic value placed on active transportation methods.
- *Contextual Factors:* Adverse weather conditions, such as cold and rain, make ASs a more attractive option compared to biking and walking. This shift in preference underlines the importance of comfort and convenience in mode choice decisions under varying environmental conditions.
- *Cost Sensitivity:* Potential users of ASs are not yet willing to pay the same ticket price as that for traditional public transit. This cost sensitivity indicates a significant barrier to the widespread adoption of AS as a basic mode of urban transportation.

  In addition to considering how would users react to AMoD, other factors can help improve the efficiency of this system. For example, a study by Bucchiarone et al. (2021) explores the collaboration between local governments and AV companies aimed at addressing the challenge of meeting last-mile needs on urban routes that are currently not covered, thereby enhancing the commuting experience. The study includes the development of a multimodal journey planning and personal travel assistance platform, named "Enablers”. This platform aims to integrate services from ASs with those offered by public and private providers, facilitating a more dynamic and collective management of mobility solutions. The methodology focuses on leveraging GeoMarketing techniques to enhance the visibility and accessibility of tourist destinations and accommodations, thereby driving an increase in hotel guest numbers.

Regarding the intention to use autonomous modes in multipolar areas, a focus for deploying both ASs and robotaxis can be considered as another potential solution to improve the AMoD system. This is because the flexibility of robotaxis can offer a particular advantage in covering diverse destinations and fill the connectivity gaps created by the ASs that work under fixed-route schedules.

The efficient allocation of travel demand to available vehicles is another effective factor in improving AMoD system. Scheltes & Correia (2017) provide foundational insights into operational strategies that enhance last-mile connectivity, specifically through the deployment of single-passenger AVs. Their agent-based simulation model, which utilizes a First In, First Out (FIFO) algorithm for allocating travel requests considers vehicle relocation and pre-booking mechanisms. The authors concluded that the proposed strategies optimize the distribution of travel requests among available vehicles and significantly reduce average travel times. Their proposed approach demonstrates the operational efficiencies that can be achieved with thoughtful planning and system design in integrating shared AVs with public transit. Salazar et al. (2018) delve into the optimization of vehicle rebalancing and customer allocation through a multi-commodity network flow model, with a case study focused on Manhattan. Their approach to integrating AMoD systems with public transit highlights the critical role of rebalancing routes in minimizing travel times for users. Moreover, the introduction of an optimal pricing strategy reveals the potential to enhance both the economic viability and user attractiveness of AMoD services, suggesting that financial considerations are paramount in facilitating the adoption of shared AVs as a complement to public transit.

Moreover, fleet size is another factor that affects the improvement of the AMoD system. Wen et al. (2018) further explored the relationship between AV-based shared mobility and existing public transit infrastructure. They indicate that an increase in the size of AV fleets correlates with enhanced service rates and diminished wait times, highlighting the pivotal role of fleet size and its management in elevating service efficiency. This observation implies that shared mobility, through its efficient use of AV fleets, could reduce the necessity for maintaining large fleets, thereby fostering a more cohesive and efficient urban transportation network.

Lastly, Chen et al. (2020) highlight the operational benefits of incorporating ridesharing into the AMoD paradigm. By demonstrating the impact of ridesharing on reducing vehicle-kilometers-traveled, their study advocates for the adoption of ridesharing as a means to alleviate urban traffic congestion.

3.6.3 Integration of ASs with Other Transportation Modes

This part of the literature review examines a broad spectrum of issues related to urban mobility, focusing on the challenges of public transit systems, the rise of micro-mobility as a form of urban mobility, and the potential of AMoD as a solution for last-mile connectivity. The main conclusions are as follows:

- Even with some improvements, public transit still does not meet the needs of people with disabilities well enough. Challenges like complicated routes, long walks, and uneven surfaces make it hard for them. Additionally, the requirement for advance scheduling in ADA paratransit services restrict spontaneous travel and limits the flexibility that is often necessary for daily activities. Furthermore, the high operational costs of these services make them financially prohibitive for many users.
- E-scooters, while popular, face significant structural and infrastructural obstacles that limit their effectiveness as a reliable urban mobility option. Issues such as low-density urban forms, inadequate connected infrastructure, and safety concerns highlight the necessity for cities to develop comprehensive micromobility strategies that integrate e-

scooters with existing transportation networks and prioritize user safety and infrastructure adequacy.

- AMoD as a last-mile solution: AMoD systems, particularly ASs, offer a promising approach to enhancing urban mobility by bridging the gap between major transit hubs and final destinations. Operational strategies, including vehicle relocation and pre-booking mechanisms, are crucial for optimizing the efficiency of these systems. However, the economic sustainability of ASs and robotaxis remains a challenge, necessitating innovative funding models and public-private partnerships to ensure their viability.
- Studies highlight both the potential and the limitations of ASs in improving public transit systems, especially in rural and low-demand urban areas. The preference for ASs diminishes with increased travel time, waiting time, and costs, indicating the importance of efficiency and affordability in their adoption.
- The dynamic nature of urban mobility, coupled with rapid technological advancements, calls for ongoing research and innovation to address emerging challenges and opportunities. Future studies should explore the integration of AV with existing public transit systems, the role of micromobility in urban transportation ecosystems, and strategies for enhancing the economic viability of new mobility solutions.

3.6.4 Summary of the Literature Review

The research team conducted a thorough review of the literature, evaluated the deployment of AVs from various perspectives, and synthesized the lessons learned from different pilot projects. In conclusion, we found that:

- The main purpose of AV deployments has been to improve connectivity and accessibility. Based on the literature review findings, their low operating speed—especially in mixed traffic environments—is a significant concern.
- Frequent disengagements and incidents underscore the need for advancements in AV technology, particularly in battery performance, connectivity, and the ability to navigate complex traffic situations and adverse weather conditions effectively.

From a technological perspective, we concluded that:

- The effectiveness of AV technology relies on the sophisticated integration of sensors, algorithms, and control systems. Sensor fusion and machine learning are key to enhancing its reliability.
- Among all available technologies, V2X communications and 5G technology are crucial for improving AV safety and navigation, ensuring low-latency and reliable communication.

From an infrastructure perspective, we concluded that:

- Providing the connectivity infrastructure is crucial for effective AV navigation because most AVs face challenges in navigation without connectivity.
- Safety-critical events, particularly at intersections and roundabouts, underscore the importance of designing urban infrastructure that accommodates AV operational needs.
- Regular maintenance of road markings and signage, along with the strategic placement of charging stations and emergency stop areas, is vital for ensuring the safe and efficient operation of AVs.
- Redesign of urban spaces, including parking lots and bridges, may be required to support the evolving needs of AV deployment. However, further investigation of the related costs and benefits is essential before changes are initiated.

Regarding public acceptance, we concluded that:

- Trust and safety concerns, especially among individuals with disabilities, highlight the need for human intervention in AVs and the importance of addressing these issues to enhance acceptance across all user groups.
- Direct exposure to LSAVs leads to more positive perceptions and an increased willingness to use AV technology.
- Different factors affect the acceptance and adoption of AVs, such as perceived usefulness, ease of use, safety, and household characteristics. Addressing these concerns can improve public acceptance.
- Cultural and demographic variations significantly affect AV acceptance, underscoring the importance of customized approaches in AV development.

Considering the regulatory perspective, we found that:

- The federal government primarily focuses on safety concerns in AV deployment and offers exemption letters for products not compatible with existing standards, although this process can be time-consuming and uncertain. This situation underscores the need for clearer regulations, especially regarding cybersecurity issues.
- States manage traffic-related aspects of AV deployment. The lack of harmonization between federal regulations and those among different states poses challenges in AV deployment due to varying traffic regulations and infrastructure requirements.
- Although addressing the needs of disabled individuals is an important concern in regulations, it has not been extensively discussed in either federal legislation or state laws.

Regarding the alternatives to AV, we concluded that:

- Public transit needs to be more convenient, especially for people with disabilities. It should offer more reliable transportation options to better serve all community members.
- Despite their popularity, micromobility face significant challenges due to structural and infrastructural limitations. Cities need to develop comprehensive micromobility strategies that are well integrated into existing transportation networks while prioritizing safety and infrastructure adequacy.
- On-demand micro-transit also face significant barriers to adoption in relation to accessibility and ease of use including lack of spatial coverage and inadequate walking access to micro-transit pick-up location. While providing door-to-door convenience and the appeal of on-demand travel, these services struggle to maintain financial and operational sustainability as ridership increases.

AMoD systems, including ASs, show promise in enhancing urban mobility by connecting major transit hubs with final destinations. These systems tackle the challenges of first and last-mile connectivity and integrate seamlessly with existing public transit networks, potentially increasing their utilization and efficiency. However, the economic sustainability and broader adoption of AMoD depend on efficient operational strategies such as dynamic vehicle rebalancing and real-time demand management. Innovative funding models, including public-private partnerships, and addressing socio-demographic factors that influence mode choice are also crucial. Additionally, AMoD contributes to environmental sustainability through reduced vehicle-kilometers-traveled, further highlighting its role in creating a more cohesive and efficient urban transportation network.

4 Conclusions and Recommendations

There is continued interest in AV technologies as well as in providing a broad set of transportation options. Technologies such as mobility on demand, ridesharing, and micromobility provide such alternative options. However, research is needed to understand how AV shuttles and other advanced technology-based options may offer solutions to the transportation challenges faced by travelers. To address this need, this research project first conducted a scan of active practice based on interviews with industry experts and stakeholders. The research team interviewed a diverse group of experts to solicit their opinions on what is coming regarding personal mobility-focused AV and the use cases for public transit. We also conducted a thorough literature review of advanced technology-based transit options such as AV shuttles, mobility on demand, ridesharing and micromobility for their advantages and disadvantages.

The interviews generated important insights related to the potential benefits and the challenges of AVs that need to be addressed. In summary, the main benefits of AV shuttles include potential safety gains due to eliminating human errors; accessibility and mobility advancement especially for individuals who depend on others for driving; and first-mile/last-mile connectivity. The main challenges include varying road quality and inconsistent 4G/5G coverage; lack of digitized infrastructure, enabling safer route choices for AVs; lack of charging infrastructure; lack of clear, standardized federal regulations and minimum performance requirements for AVs on U.S. public roads.

AV technology, which relies heavily on sensor integration, machine learning, and control systems, including V2X communications and 5G technology, remains fundamental to enhancing safety and navigational capabilities. Providing the connectivity infrastructure is crucial for effective AV navigation because most AVs face challenges in navigation without connectivity. The operational speed of AVs in mixed traffic, frequent disengagements, and incidents highlight the need for ongoing technological advancements. The success of AVs depends significantly on infrastructural support which includes not only reliable connectivity but also the regular maintenance of road markings and strategic placement of charging stations.

Issues that DOTs should be aware when planning AV deployments include roadway design and road markings to ensure consistency; need for charging stations; need to provide AV station stops; need to perform occasional sensor calibration; desire to connect AVs to signals and potentially optimize traffic signal operations for AVs. Other important considerations include the possibility of using dedicated lanes as an alternative to solving AV operation challenges in mixed traffic; developing special codes and educational programs for emergency agencies to effectively respond to AV-related events, and advocating for changes in the regulatory environment, emphasizing the importance of federal regulations to ensure safety measures and scalability.

Mobility and accessibility are key benefits promised by AVs. The integration of AV shuttles with existing and emerging transit modes presents a promising opportunity to enhance the overall transportation ecosystem, such as addressing the first-mile/last-mile connectivity challenges and providing cost-effective paratransit services. Also, AV shuttles may enhance transit resilience by providing transit agencies another option to tackle the driver shortage challenge during some economic cycles. Enhancing paratransit services could leverage AV shuttles to offer more accessible, cost-effective paratransit services for individuals with disabilities. However, there’s still the issue of AVs not currently meeting ADA standards, which poses significant limitations on their ability to fully serve all community members, especially those with specific accessibility needs.

Trust and safety concerns, especially among individuals with disabilities, highlight the need for human intervention in AVs and the importance of addressing these issues to enhance acceptance across all user groups. According to the literature, direct exposure to AVs leads to more positive perceptions and an increased willingness to use AV technology. Factors such as perceived usefulness, ease of use and safety affect the acceptance and adoption of AVs.

Considering the regulatory perspective, we found that the federal government primarily focuses on safety concerns in AV deployment and offers exemption letters for products not compatible with existing standards, although this process can be time-consuming and uncertain. This situation underscores the need for clearer regulations, especially regarding cybersecurity issues. States manage traffic-related aspects of AV deployment. The lack of harmonization between federal regulations and those among different states poses challenges in AV deployment due to varying traffic regulations and infrastructure requirements.

Generally, AMoD systems, including Autonomous Shuttles (ASs) and robotaxis, are pivotal in enhancing urban mobility by providing seamless connections between major transit hubs and final destinations. These systems not only address the challenges of first and last-mile connectivity but also integrate smoothly with existing public transit, potentially increasing its utilization and efficiency. The economic sustainability and wider adoption of AMoD hinge on efficient operational strategies such as dynamic vehicle rebalancing and real-time demand management, as well as innovative funding models including public-private partnerships. Moreover, ridesharing as a means to alleviate urban traffic congestion is promoted through reduced vehicle-kilometers-traveled, highlighting the role of AMoD in fostering a more cohesive and efficient urban transportation network.

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Appendix A – Interviewee Information

Table A1. Interviewee Information

Name	**Organization**	**Title**	**Date of the Interview**
Derric Breun and Gordon Glass	Transdev	Vice President, Operations and Director of Rail and Emerging Technology	November 1st, 2023
Clayton Tino	Beep	Chief Technology Officer	November 2nd, 2023
Dr. Rahul Razdan	Razdan Research Institute	CEO	October 30th, 2023
John Schmotzer	NVDIA	Automotive Industry Developer	October 31st, 2023
Lucienne Pears	Babcock Ranch	Vice President of Economic and Business Development	October 17th, 2023
Meghan Grela	Via	Principal (Lead Self-Driving Transit)	October 31st, 2023
Qianli Ma	Motional	Principal Engineer	October 25th, 2023
Tim Haile	Contra Costa Transportation Authority	Executive Director	November 3rd, 2023
Zayn Mashat	Ohmio	Business Developer| GTM Strategies	November 1st, 2023

Appendix B – Interviewee Notes

1. Derric Breun and Gordon Glass

In what capacity have you been involved with autonomous mobility technologies?

GGlass

So I have been involved in 11 projects to date since 2017. We have been working, just to give some background. First Transit was recently acquired by Transdev. Both companies have been involved in autonomous projects in a very similar timeframe. Combining both our expertise, we have launched over 20 projects in North America, testing various elements.

We have conducted tests in a variety of settings, including universities, business parks, downtown corridors, test facilities, and military installations.

In addition to these areas, we have also tested a range of different technologies. We have collaborated with some of the low-speed shuttles you mentioned, such as EasyMile. We also conducted a pilot with SAIC, a Chinese company. Most recently, we have worked with a stack provider, a company that integrates their technology into an FMVSS-compliant vehicle, effectively transforming it into an autonomous vehicle. The company is called Peronne Robotics.

So, I've been in the industry since 2017 and have gained extensive experience. Over the course of these years, I have witnessed significant changes in the field. I am excited to share with you our insights and learnings.

DBreun

Sure, Gordon's been in this a good bit longer than I have. I'm more on the transit side in general. I currently run the Southeast region for Transdev for all things transit-related. But I did provide services for four regularly scheduled autonomous services, utilizing EasyMile vehicles.

One was in Gainesville, another in Fairfax. We also had one with park services in North Carolina, and then Concorde, California. These were all substantial contracts over long periods of time.

We operated numerous vehicles other than the Park service, all in shared corridors. These were very interesting projects, and, as Jacob would say, we plan on having a third round in Gainesville, but we didn't quite get there. Still, we are proposing a couple of different projects as potential pilots. Additionally, we brought the EasyMile shuttle that we had purchased across the country to show many of our clients in very short one- or two-day pilots.

Based on your observation and prediction, what are the main benefits of AV shuttles?

GGlass

I think it really is just understanding where this technology is going to go in the future. So part of Transdev's goal related to transportation is looking at innovative technologies and kind of where the future is going. And we really see this as a way to develop affordable, efficient, and convenient mobility service solutions in the future. It's been, I think, we've seen a number of benefits. One of the benefits, I think, is the increase of safety in the vehicles. The vehicles, from what we've experienced, they are programmed. They have so many redundant systems with regards to safety sensors, lidar, radars, etc., that we've seen where they've actually been able to prevent incidents from occurring. So, we are very impressed with the safety element. They also, I think, will provide a number of benefits in the future with how they're used. I think we still need to develop and determine how that looks. The first-last-mile connectivity elements with the low-speed shuttles, in particular, where they're on a business campus, they work really well in a planned community. They work really well on a campus. They work really well transporting students, etc. So I think there are a lot of benefits we've seen in that element. We've also seen a huge interest in just a wide gamut of riders. So, a lot of people will travel to actually come and ride on one of these innovative solutions just to see what it's like, and the overall feedback is really positive that we've received from riders. The other piece, I guess, is that a number of the technology providers are really trying to focus on meeting people with disabilities for the ADA requirements. So most of the vehicles that we're seeing are equipped with ADA systems for users in a wheelchair. And then they're also looking at technologies for people with sight impairments or just other things where they can have different elements of verbal and different things that they can assist with. So really looking at how this will fit the whole market on that going forward.

DBReun

Yeah. To Gordon's point, Transdev's motto, for lack of a better term, is safe, reliable, and innovative. Those are the 3 main points of what we do every day: provide safe, reliable, and innovative transportation. And obviously, when it comes to autonomous vehicles, that's all about innovation. I think the key to all four of the programs that I worked on in Babcock Ranch is trying to understand what we don't know, right? We don't know how the vehicles are going to react. We don't know how the public is going to react to the vehicles. How are other vehicles going to react to the vehicles? So, you know, that's the key. How's the lidar going to work in certain situations, in different weather situations? It's interesting, you know, leaves come into play. A bag flies past the vehicle. The different settings and tendencies of a vehicle need to be adjusted. So it's a learning. It's truly testing. And again, it also, to Gordon's point, it allows the public to touch and feel what is the future. I have a good buddy of mine who is very sharp. He's an IT professional. He didn't even realize that the technology had come as far as it had. So yeah, I think that's the key to why we do it, why we want to keep doing it. It is part of the future. Gordon had mentioned robotics and the ability to outfit an existing vehicle that has passed NHTSA standards. That is a huge step forward in this entire process that is going to be a very, very big one. And he mentioned college campuses. Obviously, we were involved in Gainesville. We have a project that we're going to propose in Texas State, and again, those types of environments because youthful passengers tend to be very, very interested in technology. And it's a great way to adapt the future of transit, which is what we need to do.

Is there an operator on board?

GGlass

Yes, all of the projects we've been operating in our fixed-route shuttles. Those are all done with the safety operator on board. Transdev is also involved in a sector we differentiate. Fixed route is where you have set station calls, a route that's mapped, and it goes from point A to point B to point C. We're also working on another sector, which we call our robot taxi division. We're working with a company called Waymo in several locations. Those have moved into not having a safety operator in some of the vehicles, quite a large number of vehicles, actually. So that's the slight difference.

I think there are a few factors at play here. One is the number of low-speed vehicles that are required to be imported, with the majority coming from France or other international locations. These vehicles fall under different regulatory requirements. The reason being that they don't typically have a steering wheel or a foot brake, for instance. This made it challenging for NHTSA to determine how to regulate them. They fall under what is called Box 7 importation, which essentially requires a waiver to operate on public roads. NHTSA stipulates and validates the operational design domain, including the speed at which they can operate and any approved changes in the route. Another consideration is that these vehicles are typically low-speed and may be in mixed traffic. We strongly believe that a safety attendant is still necessary on the vehicle at this point, as they may need to take control if required. If these vehicles were operating in a contained environment with no other factors such as cyclists or pedestrians, the situation might be different. However, part of the goal is to understand how they fit into the rest of the traffic. Hence, they currently require a safety attendant.

What are the key challenges that AV shuttle projects face when it comes to successful implementation of autonomous vehicle technologies?

GGlass

As any innovative technology, there's a lot of growing things. And we've learned a lot since 2017. There's been a lot of different versions of the vehicles, and part of it is really working with the suppliers, as Derek mentioned. You know, and providing that feedback to them. A leaf falling, for instance, and that triggers a sensor, and that will trigger an emergency stop, you know. Is that the way that we want them to be programmed, etc. So this has to do with the technology providers. But I guess some of the things that we've experienced, for instance, is some of the connectivity issues. We have lost some connectivity on some of the routes. Some of them have been actually programmed even into the traffic signals.

So, linking the onboard unit with the traffic element. So that's kind of in the future where these are gonna go, there's a lot of factors involved in that. So if a traffic signal, for instance, goes down, how does the vehicle respond? So that's one for instance. The one of the major things that we see is do the road users respond around a low speed vehicle.

And typically, we've seen that some people are very compliant, and they'll follow the vehicle. Others will do merging and different things around the vehicle.

And that can be at times something that we have to monitor and understand how that's going to react. The other pieces again. Cyclists. If you're in a downtown setting specifically or pedestrians on university campuses, for instance, we've had people wearing their ear buds, for instance. People that are even oblivious of the vehicle. So the vehicle will stop, but it changes the service parameters.

The other challenge, I guess I would say, is, they are on prescribed routes. So it's very challenging to modify that route. It requires a remapping element. And so one of the areas that typically you will see and don't often know at the start of a project is construction or modifications to a road, and some of those vehicles are able to slowly be moved around the situation by the safety attendant on board.

But if it's like a 2 - 3 week construction project, typically the vehicle will run slowly, so we'll want to potentially remap that which would also require, if it's not a compliant vehicle as I mentioned under NHTSA that would require approval from them as well. So it takes some time to get those changes made into the system.

Trying to think some of the other ones that we've had. So weather is one of the challenges at times, so we've seen in every season different things. So I guess I'll start with winter. There are parameters of when the vehicle is able to operate. And that's typically given by both the vehicle technology provider, and also NHTSA. Sometimes they will specify. This vehicle can be run up to certain temperature thresholds. In certain weather conditions.

So winter is one that we've looked at. The other piece of all of these is also the battery element. So winter, you're running the heating system so that will drain your battery capacity so it can restrict how long you can operate. That's been one of the hindrances we've seen at times. One of the things when we were testing in Minnesota they had some severe snow elements. One of the things that we had to work with the city on is actually how they plow the roads.

So you know, if there's heavy snow and different things, the vehicle sees that potentially as an obstacle, so working with them on how they move those to the right locations or plow them far enough away, so the vehicle doesn't see that as an obstacle.

During spring the vegetation, though, changes so you may see a tree that's you know, grown over a certain period in different things that can change some of the mapping, and that's what we have to work with the city on, and that trimming and different things as well on that side.

And then the summer is really just the extreme heat. And again, there's sometimes thresholds on the vehicles when they can operate up to if it goes above a certain heat threshold. I haven't seen that really impact, but it does impact the battery considerably cause you're running all the air conditioning and all the systems on board.

So again, it reduces your charging capacity. So you may need to do a midday charge or run the service on a shorter period.

DBreun

Obviously, the fact that most of the manufacturers are overseas, you have to deal with customs issues, lots of red tape that you have to go through just to get the vehicle into the States. You have to return the vehicle within a certain period of time or destroy it. And, as you can imagine, vehicles are expensive. We had actually tried to see whether or not we can. We had some political support in order to actually turn the vehicles over to the university, just so they could work with them in a confined environment. But nope, they had to either be destroyed or shipped back. And then you had, in my opinion, this seems to have been a bit of a cooling-off period. A lot of the projects are funded either through Federal dollars or through State dollars. And I could tell you two and a half, three years ago, we were getting tons of requests for proposals on communities that wanted to pilot either one year, two-year, or six-month systems. And we did lots of proposals in that regard. And that seems to have cooled off a little bit. It's not necessarily the hottest topic in transit right now. So a little bit of that funding dried up. And then the actual manufacturing group, the folks that are in these units, both in the States and abroad, have condensed. There are fewer manufacturers of the technology. And so you have a smaller market to play from when it comes to units that you're gonna operate. And fewer dollars seem to be being spent on these types of operations. So that's a bit of a struggle, cause again, if you're gonna learn from the projects, you actually have to be running them. And so the number of projects that we're running are fewer and far between. So less ability to learn from what you've done in the past.

GGlass

The other thing that Derek's comments are triggering is just a lot of the regulatory elements. So, there's a lot of differences between states and operational requirements. For instance, in California, they have a weight threshold for how large the vehicle can be to operate on the roads. Also, if you have a larger vehicle, some of the states will require a CDL to operate the vehicle or a safety attendant. So that's something to think about. The other thing is some of the signage elements between states. In Minnesota, they were working on kind of working all for all the road signage to be similar. You know how this would work where driverless vehicles are in that area of the city. So that was one of the areas there to look at. And the funding, as Derek mentioned, is a big thing. So a lot of the authorities that are still looking at projects are trying to find grants and different ways to help them with the funding of that, but typically those also fall under very specific regulations. So Buy America, for instance, or ADA compliance, are some of those elements that they have to consider when looking and specifying the vehicle. And the Buy America rules out a number of the international providers because they can't meet that 80% goal for the vehicles. So that's a big challenge. And that's where moving to some of the stack technology options with like Perrone and a compliant vehicle in the US market already enables us to move forward in some of those markets and also provide a larger-scale vehicle with more seats, because most of the small shuttles are around a 6 capacity plus an attendant.

What are the areas or issues the DOTs should be prepared to address in the near future?

GGlass

Yeah, I think one of the areas just for them to really be clear on is where they're going to be operating these. So, you know, what is that Operational Design Domain that I talked about? Where are they? Are they looking to operate in mixed traffic? Are they looking to operate in dedicated routes? How fast are they looking to operate vehicles in? Are they looking to connect them to signals or not? Some vehicles now are able to read a traffic light if it's red, or do they want to actually be linked in specifically to the system? How they're going to load their passengers, for instance. So are they going to have station stops? Looking at the curves and different pullouts for the vehicles, etc., like you would do for a bus, or how that's going to look. The other piece that we've seen that the DOTs typically have a hand in is just the overall communication. So linking through their media channels with the project, working with emergency responder teams, so educating them about the vehicle. Most of these vehicles are electric, which have different requirements as well. So if there was a fire or something, how do you respond to that in the vehicle? So that's one of the areas. We touched on the regulatory, so I think that's definitely something they need to be aware of. And the funding is the other piece, just really how all the grants that are available, cause there are sufficient funds available. But how that works towards these projects?

What are the most promising use cases for AV technologies?

DBreun

Yeah, I think any kind of confined environment, universities in particular. If you, anytime you move adverse vehicles out of the situation, as few pedestrian crossings as possible, you're going to be able to improve the speed. You improve the speed, you're going to improve the willingness for folks to use it, and for communities to have the willingness to invest in those types of shuttles, 'cause that's always gonna be the biggest complaint. 'Oh, these move too slow. Why are we doing this?' But again, the reason we're doing this, it's more. I always looked at the shuttles that we're providing was more of an R&D project than a transit project, and I gotta give credit to our clients and all four instances they understood that, right? They wanted to be on the cutting edge of this technology as they moved forward.

And I think that the next big step was going to be the utilization of US-built or US-approved vehicles that were retrofitted with the necessary lidar to run in an autonomous mode. You know, I think that's the most important piece of the puzzle at this point. So at this point, provided university, or you know, the project we did for the National Park service was beautiful. Those types of applications are great. I think you do still need to do it with other vehicles running with you 'cause that's your greatest learning experience. In my opinion, we can learn about the leaves and the snow and rain, and all the other craziness that we learned about over the years doing this. But the patterns of behavior of other adverse vehicles, you know you're in autonomous mode, life is good, everything's going good, and the 18-wheeler in front of you decides he's gonna park as he needs to make a delivery, and you're stuck, right? Because the way you set up the vehicle, you'll have to get out of autonomous move mode, and then you're going even slower to try to get around the 18-wheeler. And now you're entering, maybe the oncoming traffic in order to get around it there. But that's a learning process, right? And if you're not doing it, you're not learning those pieces of the puzzle.

So it would be great to me. I'd love to see the FTA or somebody come up with a grant specific to this type of autonomous usage. Most of the time, when our grantees are looking, there's some sort of pilot program, but it's not specific to autonomous. And hey, we're gonna do an autonomous project. Great, but if they had specific autonomous grant funding, then it would have a better opportunity for our clients to be putting out requests for proposals specific to autonomous. And again, you begin the R&D process, and that's what this is. It's an R&D project, not a transit project, but it is the future of transit. What that future exactly looks like, I'm not sure I have my opinions. But it is the future of transit, and we just need to keep working on the technology, continue to innovate. But investment from the communities is important to account for stuff.

What are the latest breakthrough innovations that have improved or are expected to improve the overall performance of autonomous mobility technologies?

GGlass

I think one of the areas we're excited, too, that we've touched on a little bit is moving from the purpose-built type shuttles to the stacked vehicles. So we are in the process of working on a project in Youngstown, Ohio, where we're going to be deploying a Dodge RAM Pro Master that's been fitted with technology to make it autonomous. So the vehicle is actually able to operate at higher speeds and mix traffic, and so really just understanding how that will go forward will be very exciting. It's very different from the previous shuttles that have been in the market. So the higher speed, the greater capacity, there's more flexibility in the routes that we can operate this in, and again, it meets all the crashworthiness and all the regulatory requirements already required in the US market. So that's very exciting. And this provider, for instance, can fit this technology to, and they've done it to a number of different vehicles and Jeep Wranglers, Land Rovers, etc., in the past, for smaller or larger scale vehicles.

What is the operation speed?

GGlass

The vehicle will operate on this new project between 30 and 35 miles per hour. So it will be at higher speeds than we've typically seen with the shuttles, which are around 15 miles per hour, I would say.

What is your opinion regarding installing self-deriving kit on the vehicles?

GGlass

" So the EasyMile, and some of those probably not being as prevalent, unless they're in a very specific use case scenario. So again, if it's in a contained or a low-speed environment, they work very well. EasyMile is actually moving to a new product which is called TractEasy, where they're transporting goods on tarmacs at airports. So they're kind of moving a little bit more away from the passenger side. But I think, to your question, Jacob, I think there are two angles I would take at that. One is that I would definitely see the robotaxi type thing and the fixed route in parallel kind of working. So there are two different scenarios, the robot taxis that are working in a geo-fenced area that's, you know, they've mapped all the street elements. And they're really taking the place of, let's say, an Uber or Lyft type service to transport individuals from point A to point B, but you're still going to need the fixed route option going forward. And there are a number of providers that are working on larger-scale vehicles. There are companies in Turkey, there are companies in Germany. They're excited to see where those go in the future. Again, that can be used in mixed road use availability. There's a project that Transdev is worked on in the Netherlands, where they actually have a vehicle that's on a dedicated track. And that can go bi-directional, for instance, with ZF, that's been working very well in that environment. But again, it's not in a mixed usage environment. The requirements here are different in the US. Hopefully, that helps.

GGlass

Yeah, I think some of the, again, purpose-built shuttles potentially could go at a slightly higher speed. But in the operating environment, that's been the threshold that's been set, either through NHTSA or through the technology provider. Like I mentioned, this new vehicle that we will be testing, and it's looking like that will probably be implemented in the spring this coming year, will be going at higher speeds. So it will be in mixed traffic, connecting a transit center through the university and around a hospital area. And so it'll be very exciting for us to learn. Again, I'm not saying it's going to be perfect because I think that's something that we're going to learn lessons as we go through this, but that's one of the areas that I'm excited and Transdev is excited about, as it fits the model of what the DOTs are looking for a little bit more.

DBreun

To Gordon's point, it's all about progress, right? You know, you have time in the seat. Time in the seat creates knowledge, and knowledge creates progress. But you're not going to get the progress if you don't have the time in the seat. So this looks like a nice step forward, but we need more of them all throughout the country with different technologies. So, oh, the base of knowledge just grows and grows and grows, which needs to happen for this to have the end game, which is truly autonomous transit.

2. Clayton Tino

In what capacity have you been involved with autonomous mobility technologies?

I'm the Chief Technology Officer for a company called Beep based in Lake Nona, Florida just south of Orlando.

In my role, I'm accountable for our product development, functional program management, our technology partnerships, including our AV partners. I've also run operations and deployment for a period of time as well. So I'm a practitioner, I guess you could say. We've deployed 30 or 40 projects across the US probably in across several different platforms. So I have a good base of experience, both kind of on the fundamental sides of autonomy as well as what it means to actually implement mobility services using multi passenger form factor vehicles.

Based on your observation, what are the benefits of autonomous shuttle technologies?

Yeah, so I think when we think about autonomy in general, and we look at really trying to solve two problems first, we're big proponents of electrification. Obviously, that's not specifically related to autonomy, but we do believe it's a component of how autonomous platforms will provide societal benefit in the future. When we think about congestion, and when we think about kind of the impact of vehicles on the roadway. We believe that the shuttle form factor specifically provides kind of more both economies of scale for public transportation and better outcomes within urban settings, because we're ultimately not adding to congestion on the road by replacing one huge urban bus with a robot driven Uber. We really see it as twofold if they're electrified, obviously cleaner carbon footprint and decreasing urban congestion. And then lastly, one of the things that's not also typically spoken about is that it's very rare to provide or to see kind of accessibility use cases or vehicles that are able to provide mobility for those that may be other differently abled. So the third benefit we see is being able to provide better access to mobility for those who may have specialized requirements in terms of utilizing autonomous platforms.

Currently, are there any systems installed to support people with disabilities or the seniors?

Yeah, so we're looking at a few different things. I think the first thing people point to when they think about accessibility is obviously kind of wheelchair accommodations. So that's in our plans to bring vehicles to market that have fully automated loading and unloading and securement facilities for those who may be in wheelchairs. We're also thinking about it a bit more holistically though.

If you think about visual impairment, hearing impairment, intellectual impairment, we are focusing primarily on you know, everything that a human bus driver does today. You know, if you remove that human bias driver, how do you help with those who may have cognitive disabilities or may be hearing impaired or blind? So how can we ensure that we are able to cover kind of a wide breadth of potential passengers? You know, I think it's very common for the autonomy industry to assume that everyone has a cell phone and that the entire experience around interacting with autonomy is based on you know, a rideshare use case, you call a car it comes and picks you up to get on board and take you where you want to go.

And Mr. Roche, specifically, looking at the multi pasture form factor and considering a broader subset of passengers that may actually utilize the service. Let's think beyond the box, right. What do we have to do regarding global infrastructure? What do we have to do on board the vehicle to ensure that we're addressing all mobility needs, not just trying to reimplement the wheel using a vehicle that doesn't have a driver on board?

And are you currently operating the vehicles with a safety operator on board? And if so, is it mostly because the people feel more comfortable or because the technology is not there yet?

The shuttles are Level 3+. So they require a human onboard as the last line of defense so they are ultimately accountable for the safe operation of the vehicle. That said we do find benefit and having them on board will be transitioning to unintended or true Level 4 operations, probably by the end of 2025, early 2026.

But we will operate vehicles that are capable ahead of that transition and it's really kind of twofold. First to just validate the safety case the vehicles can be operated without drivers in specific odd, but secondly, there's some benefit to having the human onboard to explain what's going on to folks that may want to utilize the service. I think you see what is happening with some of the robo taxi providers that are entering to San Francisco. Lots of challenges with those vehicles just being able to interact with the passengers, not necessarily behaving the way you want them to. So for us, again, it's twofold. First, yes, the safety case requires that. Secondly, they're a good steward for the introduction of the technology to new environments. We think that aspect of making autonomy accessible, and frankly, ensuring that the community is supportive of it is absolutely essential for autonomy.

What are the key challenges that AV shuttle projects face when it comes to successful implementation of autonomous vehicle technologies?

You know, I'm a technologist but you know, there are a few. I think, number one is just general readiness of the infrastructure, right. I mean, it's no secret that roadway quality varies wildly.

People take for granted things like basic 3g, 4g cell phone coverage, you know, have two or three different providers and it's because as I travel around, you never know which service is going to be best for them. And that's a reality of it, just providing kind of basic autonomy service once you back in that connectivity story into things like smart infrastructure support via V2X infrastructure, traffic control, traffic tool infrastructure, or more potentially, kind of urban sensors that may be used to augment autonomy. We're just not prepared for that as a nation. You have very specific locations. Austin, San Francisco, potentially in New York.

I would say that regulatory challenges are a completely separate set of challenges, right? If you look at the readiness of Europe as an example, to adopt autonomy, there are very specific regulations that set minimum performance requirements and set standards for effectively what is required for a vehicle manufacturer or an autonomy supplier to provide a vehicle to be operated with the public on roadways. US fundamentally doesn't have that. I mean, there are programs, exceptions, that can be used to operate vehicles, but they're just that they're not codified in terms of a set of standards. You know, what are the minimum performance requirements? What are the testable standards that you have to adhere to operate a vehicle safely? And we're seeing a big tension now between states like California that are very much trying to regulate the driver aspect of it, where the federal government's not necessarily leaning as far forward as they typically would from a vehicle safety perspective. So it's really going to have to be harmonized over the next several years before we have a meaningful path to put vehicles on the roadway.

So, so it's regulations, and infrastructures are two of the most important issues

Are these the issues that public agencies and DOTs should be prepared for in the near future?

You know, I think those are probably the two most pressing, frankly, kind of infrastructure preparedness and regulatory side. There's a kind of a third where you can talk about kind of the readiness of an area or community for autonomy. If you look at the expectations of mobility in a downtown Manhattan versus San Francisco versus in Orlando, it's very different, right?

People have different relationships with the cars they have different expectations of mobility, they have different expectations of private versus public mobility services.

Like I said, dropping a bunch of Robo taxis into an urban area is not necessarily the best approach. Right? And that tends to ruffle more feathers. So, I think that kind of the third, besides infrastructure regulations, is frankly just community preparedness. Why are you doing what you're doing? Do you demonstrate that it's safe? Can you demonstrate societal benefit you help people's mindset in terms of why autonomy is providing a benefit, as opposed to just being kind of a you know, a technology boondoggle?

From your perspective what are the most promising use cases for AV shuttles? Do you see them affect the other shared mobility options, or do you mostly see them operate separately from them?

Yeah, absolutely not. I mean, we believe very strongly that autonomy has an ability to be really kind of kickstart the use of public transportation in this country. I live in the city of Atlanta full time.

And you know, there's kind of a running joke that the the number of bus lines right there run all over the city and have zero capacity, and it's for a couple reasons.

So I think for us something like a multi passenger shuttle does a couple of things. First, it lowers the total operating cost of service right, you know, paratransit or kind of specialty transit use cases that provide point to point services are prohibitively expensive to operate number one, and then number two augmenting traditional kind of quality or 40 foot bus lines of service is also very expensive. So we believe that autonomy and specifically multi passenger autonomy has the ability to really unlock access to what you consider a line transit use cases. So that's something we focus very heavily on.

You know, we don't believe in the replacement period. Just because you add a bunch of shuttles you're not taking buses off the road, it's more the exact opposite. The shuttles are becoming kind of driving a virtuous cycle to where once you get people into the system. You can keep them in the system and drive ultimately better point to point mobility outcomes.

What is the latest breakthrough innovation that is expected to improve the overall performance of autonomous shuttles?

That's a really hard question. I don't know if I could answer it. So there are a lot of different things that would become very platform specific, right. I don't know that there's any particular autonomy supplier that has solve the entire problem right.

Whether it's you know, how do you handle naturalistic driving so AVs behave the way human driver does with respect to other drivers or pedestrians expectations of their behavior, and I think the simplest use cases, approaching a four way stop, right? Everybody's been there, you kind of have that hidden communication or nonverbal communication with other drivers besides how you navigate the intersection.

We made a lot of advancements in that area kind of over the past 5 to 10 years in terms of having autonomous vehicles behave the way you'd expect the human driver to, but I think that's one thing that has to continue to improve how can you make an AV behave like other drivers expected to? I think that's one challenge. And even for pedestrians how do you provide enough visual cues of vehicle intent such that pedestrians understand how to interact with the AVs. Another area is the failure of remote operations. You know, if you have an issue with your car, they're there to take care of it. So you're off road on the exit lane. You know, deal with those kind of breakdown issues. I think that's another area of improvement. How do we start to deal with those situations when autonomy fails? If it's waiting to have an army of people on site to tow the vehicle or steer it with a remote control, that's going to be a hard challenge. So as opposed to trying to solve for every single failure scenario, how do you account for failure scenarios and have a solution in place to resolve them as they occur?

Can you talk a little bit more about the interaction with pedestrians and bicycles?

You know, I think in an area like Lake Nona, where we've been operating for many years now the community is very well aware of how the shuttles behave, what to expect from them.

Whenever we go into new areas, so people are very hesitant, right, it's to step in front of it.

They were like am I supposed to cross and we see that all the time. I mean, the shuttle will stop at a crosswalk if someone's sitting in it.

Usually, when you're at a crosswalk, if a driver stops or signals for you to pass, it's a common practice. However, this situation poses challenges for autonomous vehicles. It often requires the safety driver to manually override the AV's safety system to allow it to proceed, even when a pedestrian is present. The question is, how can we enable pedestrians to better understand the intentions of AVs so that they can make safer decisions when interacting with them on the road?

I mean, once you are no longer able to have two way communication with the thing or person that's where there's a gap. So how can you provide enough information about what the vehicles intent either to other drivers or to pedestrians such that there's kind of a common understanding that can be gained, regardless of other vehicles relying on cues from the pedestrian or the other drivers?

Do you believe that autonomous shuttles will compete with or complement the existing micromobility options like bike and scooter sharing programs? How do you see the interaction between these two modes of transportation in urban areas?

In some densely populated urban areas, options like electric scooters and bike rentals are quite practical. However, in more sprawling cities like Atlanta and Orlando, it's challenging to envision such options being successful. We see autonomous shuttles as a solution that bridges the gap for distances that are too far to walk yet too short to drive, catering to people of all abilities and weather conditions. They serve as a complement, not a competition, especially in first-mile and last-mile use cases.

Regarding the notion of making shuttles on-demand, it's important to clarify what 'on-demand' means. It could imply various things, such as demand-responsive fixed routes or a fixed route network with no stops unless there are passengers. We don't foresee moving towards pure on-demand services like robotaxis as they may not offer substantial economic or societal benefits. While there may be potential for these microshuttles to evolve into competitors in the future, it's a distant possibility. Currently, we refer to them as 'microtransit' due to the type of service they provide, which is distinct from a pure on-demand model.

Can you provide insights into the interaction between autonomous shuttles and existing infrastructure like charging stations and traffic signals? Currently, there have been challenges, particularly with left turns, where safety measures often require human intervention. Additionally, how do these shuttles interact with connected vehicles? Could you share your expectations for the advancement of this technology in the next five years, particularly in the context of autonomous vehicles' interactions with infrastructure and connected vehicles? This seems to be a specialized aspect of autonomy, and some developers have specific requirements regarding signal state certainty in their safety case formulation.

So to your point, I think unprotected left-hand turns are going to continue to be challenged [challenging]. But even something like a protected left-hand turn.

You know, how do you effectively double check right, so have a perception system that can read the state of the light but also have a secondary check through V2X communication to validate the phase of the signal?

That is one approach right, ensuring you have layers of safety to guarantee that you can validate the state of an intersection.

I think the other is some level of kind of remote confirmation. I mean, there's some folks are pursuing a use case where they have all the kind of connectivity technology to ensure they can perceive the correct state. They also rely on some level of double checking from a human to validate that it's safe to proceed.

I think realistically, we're going to have to get comfortable with the fact that other drivers are typically the problems right? It's the fault modes, the failure modes for a vehicle. Improperly perceiving and protected left hand turnout, for example, are probably a lot lower risk than a driver running around like to be blunt. And I think we have to start to think more holistically about how we deal with those kind of failure domains and risks and mitigate them.

We have encountered some of the challenges associated with operations like autonomous shuttles. We've conducted reviews of numerous pilot projects, and we've engaged with officials from the DOTs, as well as state and federal authorities. We've also interacted with various municipalities that have conducted pilot programs. The most common feedback we've received revolves around two key aspects: speed and the ability to operate effectively in mixed traffic environments. Specifically, the primary concerns are the relatively low speeds at which autonomous shuttles currently operate and the challenges they face when navigating in mixed traffic scenarios.

When I have thoughts on this challenge, I think it's primarily a base vehicle platform issue, right. I think if you look at cons of bespoke manufactured shuttles, I mean, they were not manufactured automotive grade specifications that were not mass produced to the very much kind of purpose built engineering vehicles. So things like braking resiliency, braking performance. Can you always guarantee the braking system will perform to a specific specification?

You know, mass produced vehicles, they can drive a lot faster.

Is it possible to take the same autonomous technology apply it to a transit van as opposed to a custom shuttle? The outcome might be more favorable. I don't believe that the limitations are solely attributable to the autonomy technology itself. There are other factors at play, such as the reliability and ensuring that the base vehicle performs to specified standards before integrating autonomous capabilities.

Another significant factor is the existing traffic conditions. Speed plays a critical role in why autonomous shuttles can't operate effectively in all mixed traffic scenarios. It becomes hazardous when an autonomous vehicle is traveling at 50 miles per hour while everyone else on the road is going 40. So, the issue of speed and the surrounding traffic conditions are interrelated and cannot be completely separated.

What was the speed target the next three to five years?

I'd like to mention that our target for vehicles, which includes not only shuttles but other types as well, is to achieve speeds of around 30 miles per hour and seamlessly integrate with the flow of traffic within the next three to five years. However, it's important to emphasize that this target is specific to our business and doesn't consider highway usage or broader mobility applications. In our use case, particularly for first and last-mile solutions, we are focused on achieving a speed of 30 miles per hour.

3. Dr. Rahul Razdan

In what capacity have you been involved with autonomous mobility technology?

Yeah, so I guess, I'm involved in three ways. One is the underlying semiconductors, the AI systems that these things work on. I was a CPU designer for a long time, so I'm quite familiar with it, and I work with people that design the underlying semiconductors. And then with Florida Poly, I'm involved with the validation and verification for the AI algorithms. So, how do you verify? How do you know they work? How do you know that they will achieve the goals, relative from a safety point of view? And then I've worked with SAE and IEEE and others to look at the industry-wide issues with AVs, whether it's certification, whether it's policy, whether it's even things such as business models, things like that.

Based on your observation and prediction, what are the main benefits of AV shuttles?

We are currently in the early stages of autonomous technology development, and its perceived benefits vary depending on the specific scope of application. Autonomy, in general, offers substantial advantages, particularly in restricted environments like warehouses, where it has already brought significant improvements. Warehouses are becoming increasingly automated, with the introduction of technologies like robotics.

In the transportation sector, we have witnessed the deployment of people-movers, commonly seen in airports, and the gradual emergence of shuttle services. The most advanced form of this technology is robot taxis, which are still largely experimental. Even for public transportation shuttles, while the technology is nearing viability, there are significant business-related challenges that need to be addressed.

In essence, we are at the early stages of autonomous technology adoption, and there are still many aspects to be explored and refined. It's worth noting that there are other industries, such as agriculture, where autonomy is gaining traction more rapidly than in transportation. We are in the initial phases, and there is much more to discover and develop.

What are the key challenges that AV shuttle projects face when it comes to successful implementation of autonomous vehicle technologies?

We are facing significant challenges in the development of autonomous technology, and meaningful progress is unlikely until we address these technological issues. There was a notable excitement around the DARPA challenge, with substantial funding raised and many ventures entering the market. However, we still confront three critical technical challenges, primarily related to AI components. These challenges represent fundamental technological hurdles.

These autonomous systems rely on a combination of AI components, and they often involve complex interactions between these components. Verification becomes a critical issue, especially when we're dealing with safety-critical systems. While it might not be as crucial in non-safety-critical applications like natural language processing, large language models, or recommendation systems, when it comes to safety-critical systems, the stakes are much higher. Therefore, the first step is to make progress in the fundamental science of verifying AI components, which goes beyond mere engineering.

The second thing is the way AVs are defined today is completely ludicrous because the way they're defined is a replacement for a human. And human beings are quite complicated and do many things beyond the function of transportation. And so over and over, all these companies and researchers run into trouble because the standard is a human being. Definitively, one of the indicators of reality in this context is when people shift their perspective from "this is just an autonomous vehicle" to "this AV is engaged in trucking." And indeed, it is actively involved in trucking. Additionally, a crucial sign that this transition is occurring is the presence of external signage. Much like when we label a vehicle as "student driver" to inform others that a novice is behind the wheel, similar cues will be crucial for autonomous vehicles. These external indicators will help third parties recognize the vehicle as an autonomous one, setting appropriate expectations for its behavior. It's truly absurd that AVs lack such features; it simply defies logic. We must clearly define the operational behavior of AVs to the extent that external third parties can anticipate their actions. Without this clarity, making progress in the AV industry becomes exceedingly challenging. Consider, for instance, public transportation shuttles; they stand out because of their distinctive appearance, making identification easier. However, in most cases, it's our right to know whether a Tesla is in autonomous mode or being driven by a human, particularly when the driver isn't visible. These issues aren't mere niceties; they're pivotal in determining legal liability. In many Western nations and globally, legal liability hinges on expected behavior given the available information—the crux here is the expectation. For instance, if someone were to stand in front of an oncoming train, the expectation would be that they should have known better. Thus, objects and entities in this context must assert an expectation function—a crucial aspect of this discussion. Then, the liability becomes associated with that established expectation. If an entity asserts an expectation function that is entirely unrealistic, such as behaving like an ordinary human while claiming to be just an AV, it's a recipe for disaster, as we've unfortunately witnessed. This brings me to the second critical point that must be addressed before significant progress can be achieved. It's evident that the current state of affairs in the AV industry is somewhat rudimentary. Claims of achieving Level 3 autonomy and similar advancements should be viewed with a healthy dose of skepticism. Even ADAS struggle to function effectively in most real-world situations. This, therefore, represents the second major challenge that must be resolved in the realm of autonomous vehicles. The third crucial aspect to consider is the business model. In the context of transit, autonomous vehicles often come with significantly higher costs, sometimes three times that of regular vehicles. Transit systems typically lack the extensive volume to drive down costs significantly. Therefore, we must ask ourselves, what larger-scale model justifies the implementation of AVs in transit scenarios? Various potential justifications come to mind, such as enhanced security and predictive maintenance, but these need substantial development and refinement.

We are still in the early stages of this transformation, and my sense is that it will initially gain traction in the commercial sector. For instance, in industries like mining, agriculture, and commerce-related trucking or convoying, the business models are clearer and more compelling. In contrast, the ordinary passenger car landscape is far more intricate, with a myriad of fundamental issues that need resolution. It's unlikely to see widespread adoption in this realm anytime soon.

In fact, I've made a friendly bet with my friend Brad Templeton, a corporate writer at SMI, that both Cruise and Google will eventually exit the robot taxi business. I've even sent him a note to kickstart the bet, starting with Cruise. While Brad comes from Waymo, and he's on the other side of the argument, I believe we're just scratching the surface of this technology's potential. Please don't interpret my remarks as negativity towards the technology itself; rather, I'm emphasizing the existence of fundamental challenges that are apparent, and no amount of marketing can simply gloss over these hurdles.

We're eager to understand the current status of these technologies after some field implementations and whether there have been any notable improvements in their operation. It appears that over the past two to three years, there has been a degree of stability. It feels like we've traversed a familiar path, akin to a hype cycle. Initially, there was immense excitement, with claims that these technologies were almost ready to revolutionize our world. However, as with many innovations, there came a period of disillusionment when we realized that things weren't progressing as smoothly as anticipated. We're currently in that phase.

Don't be surprised if, ultimately, the most significant market for these technologies turns out to be something unexpected, like grocery delivery robots. History often teaches us that such transformative technologies reshape markets in ways we couldn't have imagined.

I'll share a personal anecdote from my career. Back when I began, the internet was the big thing, and we, as computer makers, approached retailers with the idea that computers could enhance their operations. Retailers agreed, acknowledging the potential for faster inventory management and more. But then came along pioneers like Amazon, who suggested that we didn't even need physical retail spaces – we could do everything through e-commerce. It completely transformed the way we thought about the market. Similarly, we need to consider that the future might bring a shift where personal cars become a rarity, and everything is delivered as a service by highly automated fleets, perhaps even with distinctive signage. It's challenging to envision such a world today due to our conditioning, but think back to a time before cell phones were ubiquitous, which was not so long ago, and how dramatically that changed our lives.

As the saying goes, "In the short term, things don't change much, but in the long term, they change dramatically." Take, for example, the ease with which we can now order products globally through e-commerce. It's become so seamless that we don't even think about it. But just a few decades ago, this would have seemed unimaginable.

My point is that when these technologies intersect with markets, they often create new, unexpected variations that diverge from existing paradigms. These variations can eventually replace the old ways of doing things, but the transition may not follow the path we initially envision. While we are currently focused on automating cars, the ultimate shift might be towards a radical change in usage models. Perhaps we'll move away from the idea of owning personal cars entirely, instead accessing various services on-demand through our phones, from deliveries to school transportation. The reasons to physically move may decrease over time, with significant implications for our lifestyles.

So, as autonomy continues to evolve, it may intersect with our world in ways we haven't yet imagined. We tend to think in terms of conventional automotive manufacturers and familiar markets like passenger cars and transit. However, the real impact of autonomy might be in reshaping our world in unforeseen ways.

What are the areas or issues the DOTs should be prepared to address in the near future?

If you're a DOT, one of the critical components you lack is data intelligence. I don't mean intelligence from a cognitive perspective, but rather intelligence in terms of data. Google, for instance, possesses a wealth of information about what's happening on the roads in Florida, surpassing what the FDOT knows. Google can identify traffic patterns, assess density, and even understand intent. On the other hand, FDOT primarily has knowledge at the arterial level; it understands traffic but lacks insights into the intentions behind the movements. This distinction is crucial because it influences how you approach problems.

For example, when designing a road artery, one approach might involve expanding capacity based on observed traffic congestion. However, a more data-informed approach could consider why people are traveling from point A to B and whether shifting travel times or offering special access might provide a more effective solution. This gap in data and intelligence is the first challenge a DOT faces. If I were part of a DOT, I would prioritize establishing close relationships with global players who possess significantly more data and intelligence.

The second aspect hinges on your perspective of your DOT's role. There's a classic saying that asked the railroad industry what business they were in, and they responded, "We're in the railroad business." Eventually, airplanes and trucks revolutionized transportation, rendering railroads less relevant. The question here is whether you see your DOT as being in the road business, the transportation business, or the facilitation of goods and services transportation. It all boils down to your outlook on life and your role in enabling these shifts.

Shifts are indeed happening, particularly from the physical to the virtual realm. The fundamental question for DOTs is to what extent they should actively participate in facilitating this transition, including aspects like fiber infrastructure and network interconnectivity.

On the energy front, the electrification of transportation is undeniable, and it's likely to accelerate. Should DOTs involve themselves in enabling charging infrastructure? Range anxiety is a concern for electric vehicle owners, and addressing this issue could be a part of the DOT's role in promoting electric mobility. These are just some of the strategic considerations that DOTs must grapple with as they navigate the evolving landscape of transportation and technology.

For instance, take the scenario where an individual might opt for a truck with a 300-mile range despite having a daily commute of only 10 miles. This choice stems from the occasional need for longer trips, like going to Gainesville, which introduces a different set of considerations.

So, you're starting to grasp my point here. As a Department of Transportation (DOT), you can adopt a perspective that focuses solely on roads, road safety, and related aspects. But if you take that viewpoint, you'll arrive at one set of answers. Here's a slight aside to illustrate: consider the fire department. While it's commonly associated with fighting fires, a staggering 80% of what the fire department does today has nothing to do with fires. In reality, they primarily respond to medical emergencies, making them more like a medical service than a fire service. The contrast here underscores the importance of defining your role and scope.

When it comes to defining the mission of autonomous vehicles, it's crucial not to limit them to just "managing roads." Such a narrow perspective would significantly constrain their potential and the overall value they can bring to society. Autonomous vehicles can play pivotal roles in various domains, including energy systems and communication networks.

For instance, let's consider the concept of participating in energy systems. Instead of equipping autonomous vehicles with large, costly batteries for no specific reason, we could take a different approach. Imagine reducing the battery size to just 100 miles but gaining access to wireless power infrastructure. This illustrates how infrastructure can influence the fundamental design and affordability of a car.

A significant portion of the cost associated with electric cars lies in their batteries. By integrating autonomous vehicles into a broader ecosystem that encompasses energy, communication, and innovative business models, we can unlock new possibilities and reshape the future of transportation.

When considering this question, it involves contemplating infrastructure investments. I'd like to point out that even in the context of autonomous vehicles or ADAS, which rely heavily on sensory-based systems, the industry remains quite immature. These systems rely on sensors, and sensors require periodic calibration as they can drift out of alignment. So, the question arises: should the DOT provide support for sensor calibration? This issue extends to various aspects, such as the recognition of signage and lanes. Here, the infrastructure could potentially play a role, not as a constant, but rather as predictive maintenance islands.

Imagine specific locations where the infrastructure has full visibility of the environment. As vehicles pass through, the infrastructure can inform the vehicles about the environment, effectively acting as a diagnostic tool for the car. This is the kind of innovation that can emerge.

So, to address your question, if I were leading the FDOT, I would reflect on the mission. Should we remain focused solely on the traditional concrete aspects of transportation? Certainly, they already encompass tracking and safety systems. But should we stretch our scope further into the energy and communication domains? Perhaps even consider generating revenue from these avenues.

The current system, often based on gas taxes, has its challenges, especially with the rise of electrification. But envision a scenario where the DOT's role is to enable transportation through infrastructure. They could lay dark fiber throughout their right-of-ways and charge for it. This would make sense, as they already have the necessary infrastructure access.

So, the first question is about expanding the scope and establishing self-sustaining funding structures, given the changing landscape, with gas taxes potentially dwindling. Next, it's essential to recognize that some business models depend on infrastructure. Take, for instance, small-form-factor robots that rely on well-maintained sidewalks. In a way, the American with Disabilities Act paved the way for these robots by emphasizing wheelchair access in public spaces.

Now, if I were the head of the DOT, I'd consider being in the concrete game, facilitating energy and communication, or even enabling higher-level business models like these robots. It's a question of whether you have the capacity and funding to research and approach these issues holistically before they become problems or missed opportunities.

Most large companies have strategy teams, so my query to FDOT would be, where's your strategy team, and what are they thinking about? I haven't seen it yet. While focusing on pedestrian safety is essential, it often operates at a lower level. The key takeaway is that the world is evolving rapidly, and the role of transportation within that world is changing too. Establishing a strategy team to explore energy, communication, and higher-level business models that the DOT can actively participate in will help them remain relevant and influential. After all, who knows? In the future, we might say we don't need turnpikes anymore; we'll just run the conduit over them, reserving one lane for autonomous vehicles that take us everywhere while dedicating the rest to fiber.

So what needs to be done from both industry side and the DOT side if the sensors sometimes cannot get all the information?

I don't think there's much that can be done because the AV industry rightfully takes the stance that it can't rely on external infrastructure. It's a straightforward decision – without the necessary infrastructure in place, they won't depend on it. Moreover, consider the colossal cost required to reach the level of infrastructure needed. We struggle even to provide ubiquitous cell phone coverage, let alone the complex infrastructure AVs might require. So, the first step is to acknowledge that the AVs won't rely on external infrastructure entirely.

However, there's a secondary perspective to consider. Infrastructure can be viewed as an additive element. AVs may not depend on it, but it could act as a supplement, like a vitamin. It's somewhat useful but not something anyone is willing to pay for. This creates a bit of a catch-22 situation.

Nonetheless, there are specific scenarios where infrastructure investments can be immensely valuable. Take managed parking, for instance. Modern parking lots are highly inefficient, and finding a parking space can be a hassle. Managed parking through infrastructure could streamline this process, significantly increasing parking densities and reducing stress for users. Imagine going to an airport like Orlando, where all the parking lots are part of a managed system. You arrive at the terminal, drop off your car, and the parking management system takes care of the rest. It's a much more efficient use of space and reduces the strain on travelers.

Similarly, on highways, managed lanes for trucking could be a game-changer. While AVs would still have their own sensory systems, the infrastructure could help manage them more efficiently. So, there are instances where infrastructure investments can offer substantial value, although they may not be the grand solution to AVs' reliance.

To tackle the challenge of AVs not relying on infrastructure, we should consider the concept of smarter intersections. Many traffic fatalities occur at intersections, and implementing connectivity features could make a difference. These features could enable communication between pedestrians and drivers, creating early warning systems to prevent accidents. Additionally, parking lots are often risky environments for pedestrians. AVs and efficient parking management could reduce pedestrian presence in these lots, significantly improving safety.

In terms of industry dynamics, the automotive sector is undergoing significant transformations. Traditional automakers, aside from Tesla, find themselves with limited influence over their supply chains, especially in the semiconductor industry. They're now minor players in the supply chain. This shift toward IT-like assets is apparent, with chips making their way into vehicles. OEMs need to adapt and become more IT-oriented. If you have solutions for intersections or other infrastructure-related functions, you can approach OEMs or collaborate within open-source communities to stay ahead in this changing industry landscape. The automotive industry is experiencing a substantial transformation, with cell phone technology increasingly integrating into cars. Understanding this shift is crucial for staying competitive in the field.

4. John Schmotzer

In what capacity have you been involved with AV technologies?

John Schmotzer

I have had a rather unique career journey. I began in the defense industry, focusing on missile defense, which is a form of autonomous mobility, albeit a different one than what most people are accustomed to. After that, I spent a decade working for an automotive manufacturer, where my roles included handling connected vehicle data curation, consumption, and summarization. I also delved into business strategies related to ADAS, L2+ telemetry, and vehicle probe data.
In the last couple of years, I've had the privilege of leading a diverse team at NVIDIA, specializing in business development for enterprise infrastructure in the automotive sector. This role has given me a deep understanding of critical workflows and infrastructure requirements to support AI training for autonomous vehicles. Furthermore, I've been able to guide our customers in identifying the infrastructure they need and helping them navigate the challenges associated with transitioning from L3 to L2 and beyond. In current industry jargon, we often refer to it as L2++, as discussed among those most closely familiar with the current state of the art in the field.

Have you been involved in projects that include autonomous shuttle?

John Schmotzer

My experience doesn't directly relate to a specific project. Instead, it has primarily revolved around the strategy of crowdsourcing data collection for autonomous vehicles and supporting the geofencing approach for autonomous shuttles. In this context, my role has centered on offering infrastructure solutions, including GPU computing, storage, and related technologies, to facilitate these endeavors. If you'd like, I can provide more insights into this approach.

What are the latest breakthrough innovations that have improved or are expected to improve the overall performance of autonomous mobility technologies?

John Schmotzer

I primarily focus on a macro-level view of production vehicles that implement L2+ solutions, similar to how Tesla and Xpeng operate. Many other automotive companies are also following suit in this space. Notably, Ford and GM have adopted variants of this approach, and there is growing excitement within the industry regarding generative AI and large language models.
The latest development in the industry involves the integration of multimodal transformer models for inferencing, exemplified by a company called Wave, which has publicly announced its experiments in this area. These models aim to create a comprehensive world model that encompasses sensor fusion, decision-making, command and control, and more. They can accept inputs in the form of text, vision, and audio, adapting to various use cases. These models generate time-aligned images that project into the future, offering insights into the environment and the behavior of objects and other vehicles. The goal is to enhance decision-making processes for autonomous vehicles.

Numerous companies are exploring the potential of these multimodal transformer models, positioning them as the next generation of autonomous vehicles. These advancements have implications for various applications, from geofence shuttles to highway and city driving experiences.

What are the key challenges that AV shuttle projects face when it comes to successful implementation of autonomous vehicle technologies?

John Schmotzer

The primary challenge we face is the acquisition of accurate and high-quality data. Across the board, the cost of data collection can vary significantly, ranging from $50 per mile to the best-in-class, which achieves data collection at around 2 cents per mile. However, the accurate curation and labeling of this data for use in training sets present a large-scale macro problem. It encompasses not only technical hurdles but also business, political, geopolitical, safety, and security aspects of data collection.

There are several approaches to address this challenge. NVIDIA, for example, offers a solution called synthetic data or virtually created data, implemented through their omniverse product, Drive SIM. They create pixel-by-pixel exact replicas of real-world scenarios.

In the market, most automotive OEMs pursuing this technology implement a data collection strategy for their production solutions. They typically include a classification model within the vehicle that decides what data to collect and what to discard. Through connectivity options like cellular or Wi-Fi, they transmit this data to their backend systems, requiring embedded software expertise and enterprise compute capabilities. To create a viable dataset across their entire fleet, they need to capture approximately 200 GB of data per month per vehicle, making it a significant big data challenge within the automotive industry.

From a geopolitical standpoint, there are additional considerations such as safety, security, and privacy when collecting telemetry and vision-based data. Obtaining customer consent is crucial. For instance, Tesla must handle consent, data security, and compliance with GDPR regulations when operating in Europe. Notably, China is currently at the forefront of data collection, with a strong focus on enabling the pervasive collection of vision and telemetry data to accelerate autonomous vehicle solutions.

Addressing this challenge requires a comprehensive approach that encompasses not only technology but also political, legal, security, and privacy aspects to ensure customers feel comfortable and confident with the technology.

Has this technology already been implemented somewhere, at least as a pilot project?

John Schmotzer

Certainly, several companies have implemented in situ data collection strategies. Tesla stands out as a frontrunner in this area, demonstrating both technical prowess and progressiveness. XPeng

is another company that has excelled in developing a pervasive data collection solution. Additionally, NVIDIA has its own internal autonomous vehicle solution, which involves what I like to call "pre-production data collection." This entails using a small fleet of development vehicles within a geofenced area to gather production-quality data.
Moreover, as I mentioned earlier, there are numerous companies with which we partner. They leverage our technologies, particularly in synthetic data generation. This enables them to take their pre-production fleet's real-world data and map it into synthetic environments, offsetting the need for traditional in-situ data collection methods for generating training datasets.

Based on your observation and prediction, what are the main benefits of AV shuttles?

John Schmotzer

It's a good question. So obviously from a corporate veil perspective, we don't have full insight into the quantitative metrics of other corporations that are doing the development on top of our infrastructure. But at a high-level macro level, what we're seeing is that as a fundamental input with this new transition into multi-modal transformer models, having a comprehensive data set for training the model for being able to avoid real-world collisions and real-world events is a prerequisite requirement for those models to be accurate.

Where you find the most complexity is once you've got the core model developed. Typically what you're doing is you're looking for edge cases within the environment that are indicative of key failure modes in the road segment. For example, a deer crossing where there's a high frequency of deer crossings or a blind spot in a 4-way stop that has a propensity to create an accident. So what you really focus on then is the time to iteration or the time to market for a new model deployment and then the statistical amount of data that you have to collect to identify these edge cases.

To give you a sense, current humans are actually pretty good at driving. If you look at the NHTSA numbers, it's a couple of 100 trillion miles per year aggregate across the entire country. You only get maybe one or 2 accidents per road segment per year over those trillions of miles. So being able to find those events, those edge cases is almost a needle in the haystack type of problem. And so you can get to a 98% or 99% accurate model that can operate in most conditions, but then identifying those edge cases that are absolutely critical to train a transformer model or DNN becomes even more critical because your catastrophic failure, if you will, of the system both becomes rarer, and when they do happen, they become much more dangerous, frankly.

Is the model trained according to the environment?

In principle, yes, it's generally easier for a geofenced shuttle system to train within a highly specific area compared to a solution aiming to cover a broader range of regions. Each approach comes with its own level of complexity. Typically, L5 autonomous vehicle companies excel in operating within very specific geofenced regions, but expanding their capabilities to new areas can be a time-consuming and challenging process.

On the other hand, companies that can operate effectively across entire national or global regions face a different set of challenges. They often encounter more frequent disconnects or takeovers by the customer due to the broader and more generic nature of their training solution.

If the data is synthetic, how could it be developed to capture those edge cases?

I believe you've touched upon a billion-dollar question in the industry, and it's an ongoing debate. Nvidia, for example, adopts a customer-centric approach and heavily invests in synthetic data generation. Drawing from my previous experience at an automotive manufacturer, I can attest to the significant executive-level debate regarding whether to prioritize synthetic simulation testing or real-world testing, both of which come with their associated costs.

In the automotive industry, a single test run can cost upwards of $2 million, whereas real-world data collection can range from $75 to $35 per mile. Furthermore, generating synthetic data entails substantial expenses related to server farms and infrastructure, and there's also a risk of model drift. Large language models, for instance, tend to produce non-real-world answers when trained on artificially generated datasets.

Considering my background in business development and control systems engineering for electrical and automotive systems, I often advocate for starting with efficient, large-scale real-world data collection, particularly focused on edge cases. This real-world data can serve as a foundational dataset, enabling the creation of synthetic data derivatives to expand data elements for those edge cases without waiting for additional near-miss events or accidents to occur in the field. However, it's crucial to emphasize the necessity of having a solid foundation of real vehicle data collection to make this approach viable and valuable for model development.

When it comes to implementing this technology, do the shape and size of the vehicle play an important role?

The underlying technology remains relatively consistent, albeit with variations in configuration and training. For instance, a Class 8 semi-truck and a passenger vehicle may share the same foundational technology, but they require different models with distinct calibrations due to their unique characteristics.

Class 8 semi-trucks present distinct challenges, as they have different physics, dynamics, and blind spots compared to passenger vehicles. Moreover, they operate with varying load configurations and exhibit different acceleration and deceleration profiles. The safety criteria and budget constraints also differ, as Class 8 trucks typically cost between $150,000 to $200,000, with lower vehicle volumes compared to passenger vehicles priced at $30,000 to $50,000.

These disparities necessitate specialized sensor suites for Class 8 trucks, allowing them to afford more expensive and sophisticated sensors. Consequently, the model training and calibration for these vehicles must be tailored to accommodate their unique profiles. Camera calibrations differ, as they are positioned higher on the road in Class 8 trucks. Additionally, the decision-making framework must account for factors such as the length of the trailer and the presence or absence of a trailer.

While the general electrical design, including central compute for inference and sensor fusion, may remain similar, the primary driver of differences lies in cost. The cost of implementing autonomous technology in a light passenger vehicle significantly contrasts with the cost associated with Class 8 trucks, which can range from $150,000 to $200,000.

What are the requirements? In terms of the infrastructure, for example, is there any level of connectivity that needs to be established?

The inception of autonomous vehicle data collection predominantly involved a pre-production fleet consisting of approximately 5 to 20 vehicles. These vehicles were equipped with a substantial array of solid-state disks, typically housed in a computer located in the vehicle's trunk. The process entailed these vehicles driving for approximately eight hours in a day, followed by returning to a designated bay or garage. During the evening, they would offload the day's travel data to an infrastructure using Wi-Fi. This approach served as the standard for AV data collection for approximately the first five to ten years, originating from the early work at Carnegie Mellon University.

However, a more nuanced approach has emerged, particularly for progressive L2+ AV systems operating at scale. In these cases, in-situ data collection is performed efficiently across entire vehicle fleets without necessitating a massive bank of solid-state storage in each vehicle's trunk. Instead, these vehicles feature a more streamlined setup, typically with a few gigabytes of onboard storage integrated into a central domain controller within the vehicle. This controller incorporates software equipped with a decision-making framework, including the capability to deploy and execute classification neural networks.

An intriguing reference to this approach can be found in a research paper titled "Rapid Automotive Bill Data Analytics Framework for Structured Data," authored by Brian Mayer and others at Virginia Tech. While this paper is not directly aligned with the concept of in-situ data collection for AVs, it provides a valuable framework applicable to the deployment of classifier models in edge vehicle devices. This approach enables data harvesting within the vehicle, adding to the connectivity aspect's complexity, which encompasses both Wi-Fi and cellular connections. Managing cellular costs also becomes a crucial consideration.

Lastly, there is the overarching concept known as the "big loop" in the AV industry. This term pertains to infrastructure that acts as an endpoint for data collection, where data is stored and curated. This infrastructure also plays a pivotal role in data labeling, curation, AI training set creation, and subsequent training, replay, and simulation. These activities encompass three key workflows: data processing, AI training, and testing and validation, with synthetic data collection and curation integrated into these workflows.

Do you anticipate major companies like Tesla, Waymo, and Cruise to engage in the low-speed autonomous shuttle sector and apply this technology to public transportation?

In my perspective, I see mobility companies playing a crucial but somewhat specialized role within the broader ecosystem. We've witnessed significant advancements in sensor suite technology, primarily focused on refining system technologies. However, it's important to note that the industry hasn't reached full product maturity, even in the case of Level 5 solutions like Waymo. While Waymo has made substantial progress in the San Francisco Bay Area, there remain unresolved challenges and issues that demand our attention.

For example, the development of a multimodal transformer model solution aimed at addressing critical technological gaps, as outlined in various research papers, may require approximately five years to attain production readiness. I anticipate that progress will be driven by a gradual evolution of business value, possibly making its entry into the market through sectors like Class 8 trucks, which are currently gaining significant attention.

Considering the estimated time for product launch around 5 years and subsequent refinement an additional 3 to 5 years, it could take approximately 8 to 10 years before we have a compelling offering available in the United States. On the other hand, I expect a faster development pace in China, with Europe closely trailing behind.

Regarding public transportation, there's potential for integration between bus systems and Class 8 vehicles, leveraging existing synergies. Furthermore, the ongoing debate about the required infrastructure to support Class 3, 4, and 5 autonomy continues within the industry. Infrastructure investments might encompass deploying 5G nodes along highways to facilitate V2X communication, integrating stationary cameras at intersections, and connecting them to a broader IoT network to enhance overall safety measures.

How familiar are you with the self-driving kit that some companies are developing to install on traditional vehicles and revamp those cars? Do you trust that this technology will work?

No, I must express my strong disapproval of comma.ai's approach. In my opinion, comma.ai is an incredibly unprofessional and unsafe company. What they are attempting to do involves overwriting the Controller Area Network (CAN) communications within a vehicle. While it may be technically achievable, it's crucial to understand that CAN is designed to be robust against such attacks, effectively creating a DOS situation.

By overwriting the memory buffer for an ECU controller, they are tampering with a safety-critical system that numerous engineers have meticulously developed, adhering to an ISO 26262 standard for ASIL-D rating, specific to its function. Hacking into this system might help identify edge cases where the software lacks adequate hardening. However, marketing this as a commercial retail product and suggesting that it is road-safe for a higher level of autonomy than it was originally designed for is a perilous path, both morally and legally. This approach raises significant concerns in terms of ethics, legality, and adherence to best practices.

In summary, I believe this endeavor is led by someone highly intelligent but who may not fully grasp the implications of their actions or the reasons behind them. They lack the experience of being responsible for engineering sign-offs and releases in a professional context.

You mentioned that China probably can implement the technology faster than the US. What is the aspects that DOTs can apply?

This is quite a nuanced debate, and it's influenced by cultural factors as well. In the United States, there's a strong expectation of privacy, and the idea of someone collecting vision-based data without explicit consent can lead to significant concerns. On the other hand, China seems to have a more technology-forward approach, both at the government and cultural levels, which is supported by an abundance of technical talent.

If we focus on the United States, there's a need for education among the population about the value of data collection, how it's anonymized, and the security measures in place to protect it. Some level of policy framework, not overly restrictive, could be implemented to offer protection to automotive OEMs engaged in data collection and the development of new AI technologies for vehicles. Liability, security, and customer sentiment have always been critical considerations in the automotive industry, and addressing these concerns is essential.

From an infrastructure perspective, investments in urban or rural-based camera vision, connected vehicle hubs, and similar initiatives need to be made cost-effective. However, there's also a cultural component to this challenge. The Department of Defense in the United States should adopt a more proactive stance rather than taking a passive approach to technology development. In contrast, the Chinese government has shown strong support for its automotive industry's technological progress, which involves a more hands-on approach.

In Europe, GDPR has had a significant impact on personal privacy, which is a positive development. However, it also poses challenges for AI-driven development that involves aggregated data collection while adhering to the strict requirements of GDPR.

As you mentioned, main mobility is only serving a very niche component or part of the market. Basically, you think it's not in the high-tech space. Would big companies that have the technology, like Waymo Tesla, be interested in providing all the public transportation services, like the low-speed shuttles that we see? Why are they not doing it? Is it because of profit, or is it because of something else?

In the world of business, we often find ourselves dealing with limited resources and the need to maximize the application of those resources across various purposes, including those that serve the common good. When it comes to margins, companies like Tesla can charge a premium, such as $17,000 for an 8-hour solution. Other companies also price their capabilities accordingly. It's important to note that the technology involved in autonomous driving is expensive, with costs reaching thousands of dollars per vehicle for a Level 5 solution. In the case of Waymo, for example, the sensor stack alone can cost hundreds of thousands of dollars per vehicle, which extends the time required to break even.

Additionally, when considering the market for autonomous shuttles, especially smaller ones that might operate on a college campus, the serviceable market size is inherently limited compared to the potential market for L2+ solutions in millions of vehicles. This reality forces us to make decisions about resource allocation. For instance, if we have a budget of $150,000 per year for a well-trained, licensed driver and we can invest that money to reduce their risk of accidents by 20%, it could be argued that this allocation serves a greater societal good than providing late-night rides for a few college students. This perspective takes into account both financial considerations and the potential impact on safety.

5. Lucienne Pears

In what capacity have you been involved with AV technologies?

- I work as the Vice President of Economic and Business Development for Babcock Ranch, an 18,000-acre new town development in Southwest Florida.
- The legislature approved an independent special district in 2005, containing the entire jurisdiction of Babcock Ranch. This creates a legal entity, taxing authorities, and other values for Babcock Ranch. We anticipate that Babcock Ranch will be an incorporated jurisdiction in the future as we reach build-out, which is 19,500 homes and about 7 million square feet of commercial space, housing between 52,000 and 55,000 people.
- Babcock Ranch was founded on 8 core principles, including the environment, energy, innovation, transportation (a significant pillar), education, health and wellness, and storm safety.
- Autonomous vehicles (AVs) were introduced in Babcock Ranch around 2016-2017 to demonstrate a sustainable mode of transportation within the town. The goal is to reduce CO2 emissions, decrease the number of vehicles on the road, and promote shared transportation.
- Initially, we partnered with Transdev to navigate the new regulations in Florida and the United States concerning AVs. The early shuttles faced challenges, with speed being a significant obstacle, capping at 8 miles per hour.
- The COVID-19 pandemic and other technical challenges led to the temporary suspension of the AV program.
- Currently, we are exploring the reintroduction of AVs in Babcock Ranch, considering technological advancements that may address the speed issue. We aim to create a sustainable transit system without significantly increasing the cost of living or home ownership.

- We are seeking pilot funding to launch a program in partnership with Beep, focusing on high-demand routes during evenings and events. The study will determine whether residents would be willing to financially support AVs at Babcock Ranch due to the perceived value in their lives.

Based on your observation and prediction, what are the main benefits of AV shuttles?

During the pilot program, we noticed a couple of key factors that played a significant role. Firstly, the enthusiasm for adopting new technology was notably high among the population here. We didn't encounter the common hurdle of fear, whether it's fear of the new, fear of the unknown, or fear of something different. Instead, we found a pioneering spirit among the residents who were eager to embrace innovation.

Another important aspect we discovered was the critical mass of the population. It became apparent that we needed a larger user base to fully realize the benefits of the autonomous shuttle service.

One valuable lesson we learned was that we needed to scale up. The initial deployment was somewhat limited in terms of vehicle speed and the need for more point-to-point transportation options.

However, we also recognized certain challenges. Given Babcock Ranch's proximity to other jurisdictions, establishing public transit connections to places like Port Myers or Punta Gorda seemed infeasible due to various factors, including interstate highways, state jurisdiction roads, and multiple local jurisdictions.

On the topic of safety, we saw potential benefits in using autonomous vehicles for entertainment travel, especially for residents. This could involve providing convenient and safe transportation options for events like happy hours.

Additionally, we aimed to address mobility-related issues, particularly for individuals under 17 or those who might not be comfortable behind the wheel. Autonomous vehicles offered a solution to enhance mobility for this segment of the population.

What are the areas or issues the DOTs should be prepared to address in the near future?

Money! Our experience in the autonomous vehicle world has shown that the FDOT has done an excellent job of creating a welcoming and hospitable environment for new technology. We haven't encountered significant hurdles in our interactions with them. We are familiar with several of their innovation grants and initiatives aimed at encouraging different jurisdictions and municipalities to explore alternative mobility solutions.

However, one challenge we currently face is the availability of funding. The DOT's support is crucial, but there is a need for more diverse use cases to be considered. For instance, different scenarios such as university campuses, rural towns, and economically challenged downtown areas could benefit from AV technology. Florida's population growth has resulted in various types of residential development, with a significant shift towards master-planned communities. In this context, implementing autonomous mobility solutions in new, greenfield developments is more straightforward than retrofitting existing downtown areas. This doesn't diminish the importance of addressing downtown areas but highlights the difference in complexity.

To make progress, we should prioritize master-planned communities with mobility and connectivity in mind. This approach would involve considering how to implement alternative travel resources in these new neighborhoods. It's a productive way to set the state up for a promising future.

What are the latest breakthrough innovations that have improved or are expected to improve the overall performance of autonomous mobility technologies?

The aspect that excites us the most about reintroducing autonomous vehicle (AV) technology is the development of drivetrain systems that can be integrated into existing vehicles. For instance, consider a traditional transit van. We can essentially remove most of its internal components, leaving the steering wheel, gas, brakes, and other traditional controls intact. Then, we install an autonomous drive system that enables the vehicle to function autonomously while still retaining all the familiar features NHTSA (National Highway Traffic Safety Administration) would require and understand how to regulate. This system essentially turns the vehicle into a driver-assisted AV that can operate at speeds above 8 miles per hour. This advancement has been a game-changer for us because it allows us to achieve comparable speeds to what individuals can experience in their own vehicles.

Regarding infrastructure, one of the key advantages of AV technology, especially when compared to systems relying on guide paths or monorails, is that it places minimal demands on existing infrastructure. The main considerations from an infrastructure perspective are the availability of charging stations, which we already have an abundance of at Babcock Ranch, and the configuration of curbs at specific stops. However, these infrastructure adjustments are relatively minor and do not require extensive modifications to traditional infrastructure.

Are you facing challenges with the traffic light as well as left turns?

Interestingly, we've taken a unique approach at Babcock Ranch by designing our town with no traffic lights. We have a strong aversion to red lights because they tend to impede traffic flow and aren't particularly aesthetically pleasing. Instead, we've focused on incorporating roundabouts and four-way stops into the majority of our infrastructure. This approach has allowed us to avoid the challenges typically associated with traffic light configurations.

Are there any legal regulatory or other local or state regulations?

We have always relied on our AV partners to handle and navigate the various challenges that may arise. For instance, when working with Transdev, there were certain permitting requirements at the local and state levels that needed to be addressed before launching our autonomous shuttle service. While I may not have in-depth knowledge of the specifics of that permitting process, I can say that our agreement with beep, our potential AV partner for future pilots, would clearly designate the responsibility for addressing such regulatory requirements on the service provider.

How do you envision the residents being willing to pay for the services?

You're absolutely correct in noting that we cater to both homeowners and renters, and our objective is to offer a wide range of housing options and occupancy models. At the moment, we are primarily focusing on rental products. While it's possible to consider incorporating the cost of AV services into an amenity fee in the future, it's a significant shift to introduce a new fee when we don't yet have a clear understanding of how residents would react and adapt to such a change in their daily routines.
Our approach with the beep pilot is aimed at securing funding and, more importantly, demonstrating the benefits of AV services to our residents. We believe it's crucial to showcase these advantages first before asking residents to bear any associated costs. Currently, with factors like speed and potential operational challenges, many existing residents might not be inclined to pay for it. However, through additional pilots with improved speed and more reliable services, we aim to build trust and familiarity within the community, paving the way for a more sustainable financial model in the future.

What are the issues considering mobility specially for disabled people?

When it comes to different age groups, there are distinct challenges to consider. For the older population, the primary challenge lies in education and familiarization. Many older individuals may not be well-acquainted with autonomous vehicles and would require guidance and education to feel comfortable using them. Ensuring they know when to get on and off, and providing the necessary support and prompts, is crucial in this context. On the other hand, for the younger population, particularly children, the main concern is safety and supervision. Parents would naturally be concerned about the safety of their children during autonomous rides. Questions around who their child is traveling with and whether they are in a secure environment are likely to arise. It's important to note that these challenges may intersect with regulations related to age requirements for autonomous vehicle usage. While I may not have all the details on these regulations, it's evident that addressing the unique needs and concerns of different age groups is essential as we navigate this new technology landscape.

Considering different shared mobility options, how AVs would compete with these options?

Moving forward, the AV pilot is ready to launch quickly. Now, we're in need of funding, but it is ready to launch. We've been in discussions with other companies because we understand that this mobility system isn't going to be all things to all people. So the very first thing that came to mind that we needed to add to the system with AV would be scooters or e-bikes. We're talking to some providers of that shared service to figure out how to get deeper penetration into neighborhoods. You can't have a shuttle stop every block and still have any kind of service efficiency, right? So you have to have some hubs. But how are people getting from their homes to those hubs? So we're looking at a dispersed model of e-bikes that would complement or supplement. You could either bypass the AV altogether, or you could have that sort of setup where you get from this location up to the hub where the AV is, and then you can take the AV for a longer shuttle, right? We are in the process of working that out, working with a company. We have a proposal forward that I need to find funding for, also for that pilot program on e-bikes. Now, there are a lot of these electric Ubers, you know, door-to-door on-demand Ubers that are supposed to be this. We feel strongly that we don't want to introduce that at the same time as the AV shuttle because I think that will guarantee the failure of the AV shuttle. I think that the point-to-point on-demand electric Uber is like an incremental improvement for the sustainability of transit, a very, very small incremental improvement, but not really the solution. But then I'm going to take you one step further on the other end, and we're also spending some time trying to understand advanced air mobility. So we're talking about how to build up the electric mobility infrastructure to be able to connect to different places, not just within the neighborhood, but also to the shopping center. We recognize that there are other incredible places in the State of Florida that people might want to travel to. So how do we expand that electric mobility infrastructure to be able to be there? We need to start with looking at scooters and e-bikes. I am personally a little hesitant about the point-to-point electric Uber. But then also on the other end, looking at advanced air mobility, how do we play into the bigger region? What makes sense for us?

Have you ever considered the traditional transit options like fixed route?

When I mentioned the fixed-route option, I was referring to the traditional public bus or commute bus route concept. In Charlotte County, we don't have a comprehensive mass transit system. Instead, we have a service known as Dial-a-Ride, which provides on-demand and subsidized transportation for a $2 fee. Given this context, there isn't an existing extensive mass transit system to integrate autonomous vehicles into.

In terms of envisioning the autonomous shuttles, we are looking at them more as circulators with designated hubs and stops. These hubs would serve as central points for passengers to access the autonomous shuttles. Additionally, we are considering incorporating shared e-bikes and scooters as part of the transportation ecosystem to facilitate first-mile and last-mile connectivity, helping passengers reach their homes or various destinations from the hubs more conveniently.

It's important to note that the autonomous shuttles follow specific routes with defined timing and stops, resembling what you might call a fixed route, albeit on a smaller scale and tailored to the community's needs.

What about the police and emergence response to the AVs?

The initial step in our operations was to provide regional education for all law enforcement, fire, and public safety personnel. This wasn't limited to those who might encounter autonomous vehicles at Babcock Ranch but was extended as an open invitation to anyone in these roles interested in learning how to interact with AVs. Throughout the pilot, which is expected to span

18 months, we have scheduled several training sessions, and I believe we currently have three of them planned.

6. Meghan Grela

In what experiences have you been involved with AV technologies?

- Rideshare and fleet management part of AVs
- Not involved in manufacturing side
- Micro-transit on-demand, working with institutions/entities than direct to consumer.

Based on your observation and prediction, what are the main benefits of AV shuttles?

- Address labor shortage issues with transit agencies
- Improvement in traffic safety
- AV as a new variable that can draw car commuters to public transit options that would have otherwise not switched, thereby reducing traffic.
- On-demand options that supplement the transit have to meet the same ADA standards, whereas robotaxis do not need to. The manufacturing of wheelchair accessible shared use vehicles is becoming more efficient.

What are the key challenges that AV shuttle projects face when it comes to successful implementation of autonomous vehicle technologies?

- Availability of the technology, limited providers, less flexibility to customize for various ODDs (Operational Design Domains)
- Regulatory frameworks

What are the most promising use cases for AV technologies?

- Rideshare and micro-transit models better suited to address environmental and equity issues
- Replace or enhance existing transit options that may be inefficient. Either through new routing methods or through new form factors.

What are the areas or issues the DOTs should be prepared to address in the near future?

- Studying the market and be prepared for upcoming companies
- Incentivizing non individual modes (transit) to cater to people with mobility disadvantages and from all income levels

Connectivity-

- Big tech companies are not incentivized to take advantage of connectivity
- AV providers need to be educated about the use cases where connectivity can save lives

7. Qianli Ma

We'd like to know on what capacity have you been involved with autonomous shuttle technologies?

So, to give you an overview, I've been working in the industry for about six and a half years since earning my PhD in mechanical engineering from Johns Hopkins. When I first started, my role involved research and engineering, primarily focused on developing algorithms for planning and control.

I spent a significant amount of time diving into research papers, coding those algorithms into prototypes, and ensuring their safety for deployment in vehicles. I continued this work for roughly four years before transitioning to a different role, which involved partnering with major rideshare companies.

For the initial three to four years, my primary focus was on building and refining the core technology of our product. Afterward, I shifted my attention to making this product accessible to the general public and passengers. Currently, I lead a team that's dedicated to expanding the deployment of this technology across multiple cities.

So, in a nutshell, that's what I've been up to over the past six and a half years.

Based on your observation have you seen any benefits from implementing autonomous shuttle technologies?

Yes, there are two significant advantages to using technology in this context. Firstly, there's a major emphasis on safety. Even though human drivers are generally quite skilled, accidents still occur regularly due to human error or lapses in responsibility. We all know that we're not infallible, and that's why having a vigilant machine constantly monitoring the road can ultimately enhance safety, especially for large-scale operations like city-wide truck deliveries.

Digging deeper into this, the safety bar set by human drivers is already quite high. I've come across statistics indicating that there are approximately 1.5 accidents for every 100 million miles driven by humans. This sets a challenging standard for autonomous driving vehicles to meet, but it's a crucial goal to strive for.

The second notable benefit is economic efficiency. When you use services like Uber or Lyft, you're paying for a human driver's time, salary, and insurance. By eliminating the risk of human error or the need for drivers altogether, you can significantly reduce costs. Moreover, humans can make route mistakes, such as missing a turn suggested by a navigation system, which can lead to inefficiencies in time and fuel consumption. Autonomous systems are programmed to consistently choose the most optimal route, whether it's for fuel efficiency or considering traffic flow. This not only cuts down costs but also enhances overall city functionality and efficiency.

But is it a prediction or is it something that you have already observed in the field?

Absolutely, I understand your perspective. Fuel efficiency is indeed a critical factor, but it's not the primary focus for deploying this technology at the moment. It's a challenging and largely unsolved problem in the industry. While we have witnessed some companies making strides, especially this year, where we've seen the launch of truly driverless vehicles, many others are still grappling with the complexities involved in achieving optimal fuel efficiency. So, while it's a goal on the horizon, the main focus right now is addressing the immediate challenges and making the technology safe and reliable.

What about safety and mobility?

Observationally speaking, I believe we need more data to confidently claim intellectual safety. However, when it comes to the practical processes involved in deploying vehicles on the road, companies take extensive measures.

Typically, companies run millions of miles of simulations encompassing various scenarios stored in their databases. This thorough testing ensures that the vehicles can handle all possible cases before they hit the road. In this regard, it's worth noting that human drivers don't undergo the same rigorous mental simulations before getting behind the wheel; they simply take an exam and start driving.

At the current stage of autonomous vehicle development, fuel efficiency isn't the primary concern. While making intellectual claims about safety requires more data, companies are taking practical steps to ensure safety before deploying autonomous vehicles on the road. These steps involve running extensive simulations with various scenarios to guarantee that autonomous vehicles can effectively handle different situations. Unlike human drivers who lack the experience of conducting such simulations in their heads, autonomous vehicle developers rigorously test their systems before deployment.

What do you see as challenges in implementing these technologies?

Yeah, there are indeed a lot of challenges in this field. I began my career working on electronic control systems, and it's widely recognized that planning algorithms, prediction, and perception are at the core of autonomous technology. These areas are also the most challenging because they involve solving previously unsolved problems.

If we compare it to other industries, like car manufacturing or software development, there's a stark contrast. Traditional car companies have clear requirements and processes for building and validating vehicles before mass production. Similarly, in software, companies know how to develop and deliver products like web browsers to customers. But with self-driving cars, it's a different story. There are no clear requirements for the features or behaviors a self-driving car should have, and there's no established process for validating that a company's claims about its vehicle's features are accurate. This complexity is a significant hurdle.

Planning algorithms, in particular, pose a major challenge because they serve as the vehicle's decision-making "brain." They process inputs from perception and prediction modules to determine how the vehicle should respond – whether it's accelerating, decelerating, turning left or right, or stopping at a traffic light. The challenge lies in deciding whether we can trust the output from the upstream algorithm and whether it's the most optimal course of action. If trust is lacking, determining the threshold or level of trust required for making probabilistic decisions becomes a complex task.

Looking back seven or eight years ago, many companies could demonstrate their vehicles slowing down at traffic lights or changing lanes to avoid obstacles. However, these were essentially demonstration cases. The real challenge lies in handling a multitude of edge cases. This necessitates the curation of massive amounts of data and continuous system training.

When we consider achieving the safety benchmark of 1.5 accidents per 100 million miles, similar to human drivers, it raises questions. Do we really need to drive a hundred million miles to prove a point? Is it even feasible? These questions add to the complexity of deploying fully autonomous technologies on public roads.

So, in essence, the challenges we face in this industry are substantial and make the deployment of truly self-driving technologies on public roads a formidable task.

Do you see these challenges only in the low speed autonomous vehicles?

Yeah, there's a prevailing opinion in the industry suggesting that handling high-speed driving, like on highways, might be technically easier with autonomous technology. This perspective has led to the emergence of numerous companies, particularly in the trucking sector, focusing on logistics and highway driving. From my point of view, it's a bit subjective, as it varies from person to person.

Technically speaking, implementing autonomous algorithms for highway driving may indeed be considered safer or more manageable. However, the stakes are higher because when accidents do occur on highways, the potential for severe fatalities is greater compared to urban scenarios with lower speeds. Urban driving, on the other hand, can be quite complicated, especially depending on the city you're in. Many human drivers often fail to adhere to traffic laws, which adds to the complexity.

In essence, if all vehicles on the road were suddenly replaced by autonomous cars, the problem might seem easier. But the challenge persists because we still have human drivers who don't consistently follow the rules. This dynamic creates a unique challenge in the deployment of autonomous technology. It's indeed an interesting contrast to consider.

What are the latest breakthrough innovations that have improved or are expected to improve the overall performance of autonomous mobility technologies?

It's quite fascinating to see how breakthroughs in technology have the potential to enhance low-speed performance in autonomous driving. Recent advancements in the field of machine learning and deep learning have been a significant driving force behind these improvements.

Looking back about seven to nine years ago, especially in the realm of perception and prediction, the concept of prediction was virtually nonexistent. At that time, our focus was primarily on perceiving the vehicle's current location rather than projecting its future path. Most algorithms used in the industry and research were still rooted in geometry-based approaches, with limited reliance on deep learning or training data.

However, in recent years, there has been a noticeable shift. Nearly all companies in the industry and universities have embraced deep learning technology, recognizing its efficiency. From my own experience and interactions with industry peers, it's evident that deep learning has been particularly effective in urban and low-speed scenarios, mainly due to the abundance of data collected in these environments.

In general, a learning-based approach holds great promise for improving performance. Initially, many algorithms were rule-based, but we are gradually transitioning toward a data-driven approach. However, there may be a middle ground – a hybrid approach – that combines elements of both rule-based and data-driven methods before fully adopting a pure data-driven approach.

What are the most promising use cases for AV technologies?

The way autonomous vehicle services are organized can vary significantly, with options like on-demand services or fixed-route models similar to traditional buses.

The choice of service model is a critical factor, and that's why different companies have different approaches. For instance, some companies, both in the US and elsewhere, are focusing on autonomous driving for buses or minibuses. These vehicles typically follow fixed routes and maintain moderate speeds, making deployment more manageable. Additionally, these models cater to a structured demand.

On the other hand, many companies, especially in the US, are concentrating on the Robo taxi service model. With Robo taxis, there are no fixed routes, providing passengers with more flexibility. However, this approach requires a different strategy to address the diverse demands of passengers.

Our company has a unique situation, as you can find online. We operate a fleet of vehicles in Las Vegas, a city known for its major thoroughfare with numerous hotels and casinos on either side. While it's not a fixed route per se, it's not entirely free either, allowing us to strike a balance between structured service and the technology required for deployment. We aim to provide a service model that meets both the needs of our American customers and the technological requirements for successful deployment.

We're quite curious about the distinctions among the prominent autonomous driving technologies represented by Cruise and Waymo. Specifically, could you elaborate on how these technologies differ, especially considering that companies like Cruise and Waymo employ heavily encrypted vehicles?

Great question! First, let me clarify our approach at my company. We're not simply trying to retrofit kits onto existing platforms. While that may have been the case two years ago, we've since formed a partnership with Hyundai. Our current goal is to introduce the next generation of fully autonomous vehicles using a Hyundai platform, focusing on mass production.

I understand your point about some companies retrofitting existing vehicles and adding software or hardware. I'd be happy to address these cases one by one. Also, I recently came across some surprising news regarding Cruise's license suspension due to an accident, though I won't comment on that specific incident.

In general, when a new technology emerges, doubts and concerns are natural. No product, no matter how intelligent, is flawless from day one. We've seen similar situations in the past, not just with Cruise but also with other companies. These are like the hiccups in the middle of progress, and we'll overcome them.

In my personal opinion, I firmly believe that robot taxis are part of the future. Machines will continue to learn and improve. The power of continuous learning, whether through rule iteration, data analysis, or simulating challenging scenarios, enhances the intelligence of autonomous vehicles. I anticipate a time when we witness a significant breakthrough, similar to what we've recently seen with chatbot technology.

The goal of having driverless vehicles on the road is within reach. It may take time, but it's a part of the future I see coming.

Regarding the second case of integrating software or hardware into a platform, I believe that's a bit of a dated approach, often used for showcasing specific technology capabilities. With software revolutionizing vehicle production, it's essential to design hardware, firmware, and software from the beginning to be suitable for both electric and non-autonomous vehicles, rather than adding separate components later.

Lastly, the concept of shuttles or buses is intriguing. In countries with high population density like some Asian countries, where public transportation is widely used, it could have potential. However, in the US, I believe that the Robo taxi service model is one of the more promising options. Another viable service model, despite not being purely a technological consideration, is trucking.

However, it's essential to keep pushing the boundaries to enhance public services using autonomous driving technology. While Robo taxis might be at the forefront in terms of popularity, there's certainly room for exploration and innovation in various service models.

What is your opinion on retrofitting kits for traditional vehicles?

You know, some companies have been all about retrofitting kits for regular cars, but my company, well, we've taken a different route. We've teamed up with Hyundai to create the next-generation fully autonomous vehicles. It's a shift away from the kit approach.

Those kits, they had their time in the spotlight, but it seems they might not be the main path forward anymore.

Now, when it comes to Robo Taxis, like Waymo and Cruise, there have been some bumps in the road, like Cruise's licenses getting suspended due to an accident. But, you know, despite these challenges, I'm pretty convinced that Robo Taxis are still a big part of our future. We've got technology continuously learning and improving, which is pretty exciting.

The real power lies in this ongoing learning process and data-driven methods that will keep pushing Robo Taxis forward.

As for low-speed autonomous shuttles, they could work well in densely populated areas with lots of people using public transport. But in the US, it's Robo Taxis that are taking the spotlight. They offer that flexibility and might just win the popularity contest.

While Robo Taxis and trucking might be the stars of the show right now, we can't forget about exploring how autonomous tech can revamp public services. There's potential there, too.

Do you believe that in the next five to ten years, there's a possibility for significant advancements in self-driving kits and low-speed autonomous shuttles that could potentially allow them to catch up with the performance of Robo Taxi technology, or do you think the substantial investments and resources dedicated to Robo Taxis put them at an advantage that's hard to overcome?

Absolutely, it's interesting to consider how some people are keen on using self-driving kits to retrofit existing vehicles. I've had some experience with those kits back when we were in the demo stage. Additionally, I'm aware of companies that provide cameras you can install on the car's windshield or other parts to connect and control the vehicle. Now, for something like level two or maybe close to level three autonomy, that might be workable. However, when we're talking about high safety standards and complex integrations, it becomes challenging. Achieving seamless software compatibility, especially in a safety-critical context, isn't straightforward. To put it into perspective, think about how we have numerous social media apps today. Imagine trying to create a super social media app integrator that can handle all of them together, allowing you to manage everything from one place. It sounds convenient, but making it work seamlessly across different platforms is no easy feat.

8. Tim Haile

On what capacity have you been involved with AV technologies?

Hello, I'm Tim Haile, the Executive Director of the CCTA. CCTA is a county agency located in the East Bay, one of the nine Bay Area counties in California. Our county has a unique way of funding transportation projects through voter-approved sales tax measures. CCTA's role is to collect these sales taxes and use the funds to plan, implement, and finance various transportation projects and programs. Our primary focus is on managing and reducing congestion, enhancing mobility, and ensuring equitable transportation access for all residents.

CCTA doesn't directly operate transportation services; instead, we are responsible for planning, funding, and overseeing infrastructure projects. One distinctive aspect of CCTA is that we own and manage one of the largest secured autonomous vehicle testing facilities in the country, known as GoMentum Station. This facility has been in operation since 2014, and you can find more information about it on our website.

Based on your observation and prediction, what are the main benefits of AV shuttles?

We strongly believe that autonomous technology can improve safety, enhance mobility, and contribute to climate goals, especially with the shift to electric and shared mobility solutions. GoMentum Station has been pivotal in providing a front-row seat to the future, allowing us to learn from the latest technologies and their potential use cases.

One key area we're exploring is first and last-mile transportation within our communities. Many trips are within two miles, making micro-transit and shared autonomous mobility a promising solution. In 2016, we imported the first level four shared autonomous vehicle in the United States, an EasyMile shuttle from France. We were the first agency in California to operate it on public roads and now offer a free shared autonomous vehicle service within a 600-acre business park, connecting businesses, downtown areas, and transit centers.

CCTA received an Automated Driving System grant from the Federal Transit Administration (FTA) in 2019 to implement three projects. One involves deploying a shared autonomous vehicle in a senior community called Rossmoor, addressing the transportation needs of elderly residents. Another project focuses on providing paratransit autonomous shuttle services to a county hospital to improve medical appointment attendance. We're also developing a dynamic personal micro-transit network, connecting four cities through a 28-mile network of small shared autonomous pods.

Lastly, we're collaborating with Nissan, Verizon, and UC Berkeley to explore how connected autonomous vehicles can enhance traffic flow on highways. By using a small number of autonomous and connected vehicles as "pace cars," we aim to harmonize traffic and improve freeway efficiency. These projects reflect our commitment to leveraging autonomous technology for real-world benefits and enhancing transportation options for our communities.

What are the most promising use cases for AV technologies?

We recently organized a community event series during the past summer, where we brought a shared autonomous vehicle to all 19 cities in our region. We engaged with the community to discuss this technology and how they perceive its potential benefits, especially for trips of less than two miles.

What we found was that community members see the shared autonomous vehicles as a valuable solution for connecting them to transit stations, like BART stations, and to various points of interest such as movie theaters, downtown areas, grocery stores, and community centers. They particularly appreciate the idea of a point-to-point system where the shuttle picks them up in front of their homes, eliminating the need to find a bus stop or plan their journey around fixed transit routes.

The shared autonomous vehicles are seen as a way to serve the underserved population, including those who lack access to transportation. We believe that autonomous mobility will have a direct impact on equity, accessibility, and improving the lives of underserved communities. In Contra Costa County, 15% of the population is over the age of 65, and this percentage is expected to double by 2035. This means that a significant portion of our population will depend on others for transportation. Shared autonomous vehicles can offer these individuals more freedom and independence.

Regarding feedback from elderly users, they are genuinely excited about the technology. We even took some seniors to GoMentum Station to show them the shared autonomous vehicle, and their response was, "We want this now!" They see it as an opportunity for greater freedom and independence, which is particularly important in a county where a significant portion of the population is aging.

We conducted a travel behavior study that showed 70% of respondents are excited about the future of autonomous mobility. While there are safety concerns, both in terms of vehicle safety and personal safety, these concerns are outweighed by the overall excitement and positive perceptions of the technology. As people become more familiar with and experience autonomous vehicles, they tend to feel safer and more comfortable with the technology. Personally, I've ridden in many autonomous vehicles and am a strong advocate for this technology because of the positive experiences I've had.

What are the key challenges that AV shuttle projects face when it comes to successful implementation of autonomous vehicle technologies?

When we talk about the challenges in autonomous vehicles, I usually categorize them into three main areas. First, there's the regulatory environment, which can be quite complex. Second, there's the issue of public acceptance and education. People need to understand how the technology works to embrace it fully. To address this, we took autonomous shuttles to all 19 cities to let people see, touch, and experience the technology firsthand. This kind of interaction helps bridge the gap between the public and autonomous vehicles.

However, public acceptance can sometimes be challenging due to misunderstandings or even resistance, as we've seen in cases like the cones on the hoods of Cruise vehicles in San Francisco. These incidents highlight the need for comprehensive public education.

The third challenge is mixed traffic. We must ensure that autonomous vehicles operate safely alongside human-driven vehicles. To address this, we carefully evaluate the routes for autonomous vehicle projects, test them in various scenarios, and provide extensive training to those who interact with the vehicles. It's essential to focus on use cases that align with the current capabilities of the technology while recognizing that technology will continue to evolve.

To overcome these challenges, it's crucial to digitize infrastructure and enhance communication between traffic management centers, digital infrastructure, and onboard vehicle systems. This connectivity will enable better coordination, especially in complex situations or emergencies. Additionally, with the evolution of artificial intelligence and increased simulation testing, we can better prepare autonomous vehicles to handle edge cases.

While companies like Waymo and Cruise are already operating in certain areas, achieving full-scale deployment will take time, likely around a decade. This timeline accounts for the need to address regulatory hurdles, educate the public, and develop the necessary workforce. The technology is ready for specific use cases, such as our project in Contra Costa County, where we've seen success in providing autonomous shuttle services to the public.

In conclusion, the key is to match the technology with the right use case and gradually scale its deployment while addressing the challenges in regulation, public acceptance, and mixed traffic scenarios.

What are the latest breakthrough innovations that have improved or are expected to improve the overall performance of autonomous mobility technologies?

I've already mentioned it, but I believe that artificial intelligence will be the most significant game-changer in the realm of autonomous vehicles. It will revolutionize how these vehicles interact with infrastructure and users. Currently, when an autonomous vehicle operates, it stays within its predefined Operational Design Domain. If it encounters something outside of this domain, it can become confused and simply stop.

What I hope to see with the integration of artificial intelligence is that these vehicles will become more adaptable. They'll be able to handle those tricky edge cases that fall outside their typical parameters. This shift will likely be the most substantial game-changer in the field of autonomous vehicles.

How do you currently tackle the challenges associated with lower speeds, frequent slowdowns, or stops in autonomous vehicle operations? Is there always an operator on board to address these situations?

Cruise and Waymo currently have permits to operate without a driver. Remote operations play a crucial role in handling situations where autonomous vehicles encounter unexpected edge cases. This is essential because planning for every possible edge case can be challenging, and when the vehicle doesn't know how to handle it, it may come to a stop. So, having someone remotely monitoring and operating the vehicle becomes critical in these situations.

Addressing challenges like frequent slowdowns and stops, especially at lower speeds, requires careful route selection. For instance, the shared autonomous vehicle we are currently operating has a maximum speed of 12 miles per hour. Due to this, regulatory requirements demand that it can only operate on roads with posted speed limits of 25 miles per hour or less. Therefore, ensuring that the technology is applied to routes that match its capabilities is crucial for safe operations.

In addition to route selection, the presence of a safety attendant on the vehicle is also mandated by regulatory bodies. This ensures that there is a human operator available to intervene in case of unexpected situations. Remote monitoring and remote operations, akin to an air traffic control setup, are essential components of handling autonomous vehicles in mixed traffic. Having a command center to track vehicle locations, monitor their status, and collect valuable data is vital for enhancing safety and efficiency.

Moreover, data standards and requirements are significant in this context. Leveraging data specifications like the multimodal data specification developed by the Ultra Mobility Foundation enables us to gather valuable information about vehicle operations, disengagements, slowdowns, and stops. This data is crucial for understanding disruptions and incidents in the transportation system and can aid in better decision-making, such as dispatching assistance or towing vehicles in case of breakdowns.

What DOTs should be prepared for in the near future?

Preparing for the future of autonomous vehicles involves several key steps and considerations. One crucial aspect is the digitization of infrastructure, which includes creating a connected network that allows vehicles to communicate with each other and the infrastructure itself. This connectivity will play a significant role in the safe and efficient operation of autonomous vehicles.

Another important aspect is regulatory change. The current regulatory environment poses challenges, especially concerning vehicles without traditional controls like steering wheels, brake pedals, or gas pedals. The federal government needs to update and clarify regulations to support the deployment of purpose-built autonomous vehicles. This includes addressing issues related to self-certification and considering third-party validation models similar to those used in Europe.

Additionally, a federal regulatory framework should be established to provide consistency and clarity across states. Currently, states have been creating their own legislation, resulting in a patchwork of regulations that can hinder the scaling of autonomous vehicle technology.

Another consideration is the "Buy American" requirement for federal funding. This requirement mandates that federal funds be spent on components made or built in the United States. Evaluating and potentially revising these requirements can impact the sourcing of components for autonomous vehicles.

9. Zayn Mashat

In what capacity have you been involved with autonomous mobility technologies?

Yes, from the technology perspective, I can offer a different viewpoint since I don't directly work with the technology itself. My role primarily involves business development. Are you familiar with what we do? Have you had a chance to look into our work?

Essentially, our shuttles serve as first and last-mile delivery for passengers. They function as people movers. However, Ohmio aims to be a solution provider rather than just a vehicle seller. Our focus is not on a 'set it and forget it' approach. Instead, we strive to understand the specific requirements of each project or area we serve. We then retrofit and customize our buses or shuttles accordingly. This means that two shuttles are the same; each is altered and modified based on the unique needs of the project.

My involvement with autonomous mobility technologies always begins with a deep understanding of the project's landscape. I work closely with our R&D team to address any technological gaps or requirements. My perspective and approach may differ from that of Mohammed, our founder, as I prioritize understanding the project first and then integrating Ohmio and our products to meet its needs.

In the past, I have also worked with research and advisory firms, acting as a liaison to identify gaps and apply the findings to our research in the field of autonomous mobility. This is the capacity from which I approach you.

What are the key challenges that AV shuttle projects face when it comes to a successful implementation of autonomous vehicle technologies?

Yeah, most certainly. So, when it comes to building and designing projects, and when we are working with folks who do not necessarily understand autonomous mobility itself, one of the biggest challenges is educating those about technology. People often approach us with plans to use our shuttles at 50 miles per hour. However, for our autonomous vehicles, especially those of our capacity, there are several challenges and retrofitting requirements to ensure compliance with such speeds. Educating customers about what's feasible and what's not is a significant aspect of my role.

From an implementation perspective, designing a safe path for a specific speed is a continuous challenge. In the design phase, It's not just about saying 'yes' to a project but actually helping design it and even the retrofitting process. For instance, if we need to include sensors on the guideway, many customers may not understand the technical requirements or the necessary retrofits for a specific path. My role involves educating them about why certain things need to be installed, and why certain precautions need to be made.

and also, educating them about the current limitations of the technology. For example, 50 miles per hour is not quite ready for this kind of technology at present. We shouldn't be geared at doing that.

What kind of customers do you have?

Let's talk about North America because that's where my domain is more focused - public agencies. Yes, a majority of them right now are public agencies, but with that said, there has been an increase in interest from more private agencies looking at this technology as well. For example, gated communities and retirement homes or retirement communities are looking at it. considering it as a way to make it easier for their folks to get around. There's been an increase in this trend. Even some hospitals have shown interest in our technologies. However, at the moment, yes, it's primarily public agencies.

Would they keep the service model as public autonomous shuttle, or is the fee going to change? In that case it's mainly public.

What are the challenges that you face with public agencies in North America? And what are the areas or issues the DOTs should be prepared to address in the near future?

I think, from my perspective, we need more projects every year. You know, there's not enough projects for our technology just yet. So, it's yes, it's the early stages, but for it to really develop, get fit, and move faster, we need more projects with more local government bodies.

The second thing, I would say, is that in our space of autonomous shuttles, there's a very niche community of people that can actually help and manage these technologies. So, we need an increase of service providers that can partner with us. It's kind of like a monopoly or a very small market at this stage. Getting more voices and more players in the market and a bigger ecosystem is one of the biggest challenges. From my perspective, we're always looking at creative ways to address those challenges. Who's going to manage all of these vehicles? Does it have to be the company that's building them? Does it have to be a third-party agency? If it is a third-party agency, there aren't enough of them. There are maybe one or two, and that's it. There are some other folks that claim they do it, but they don't really do it. So it's just really getting a bigger ecosystem of players that can help with the technology and services. Technology is one of the shortfalls, and we're creatively working on it.

And this is a study, so I'm not at the liberty of saying what we're doing right now. But there are some creative ways that we've thought of to build that ecosystem out. I would say, keep an eye out on it. Yeah.

What are the areas or the issues that the duties and public agencies generally should be prepared to address in the near future?

Letting new players in and being more open to it. Right now, it's a very niche market. Now, from that perspective, yeah, it would go to those. So I would stress those two, from my perspective, at least from a business development perspective. It's really those two things that I see. You know, we need more projects and more project adoption from those, to begin with. But the second part would be kind of building out that ecosystem, or at least partnering with folks like us when it comes to building it out, as opposed to just pointing to the same solution and doing it over and over. Because if we stay with a small ecosystem, how are we going to improve the service and make it better? Right? We need a little bit more competition. So, yeah, I would reiterate those two again.

Any other type of challenges, such as technical operational challenges or infrastructure challenges, that may hinder the successful implementation?

More charging infrastructure for sure. We, and you know, depending on what state you're looking at, there's more in some places than others. But yeah, definitely like every project I've worked with, it's either delayed because, hey, we haven't figured out how we're going to do the charging infrastructure or where we're going to charge these vehicles.

I would say that maybe even more again when it comes back to that ecosystem service stations for these types of vehicles. Especially with our technologies, at least, we essentially get a permit to operate in a certain area, right, or a certain path. So, another challenge is, how do we get the vehicles from point A to Point B that's not part of that path. So we can drive it in manual mode, in the location where it's not part of the map. So, there are a lot of restrictions in place, and fair enough some of it is for public safety, so that makes sense. But there needs to be more creative ways of how to service these vehicles, how to charge them, getting more infrastructure in place.

And when we're talking about charging infrastructure, maybe some of it needs to be dedicated for vehicles like ours, especially as more people look at first-mile, last-mile delivery solutions and things like that. So, that would be one.

What are the main benefits you have seen so far regarding the AV shuttles implementation?

If we're talking about safety, we have a 'knock on wood' 0 incidents or safety concerns. So that's already an improvement from what you could expect. So that's one.

I think we're also very early in autonomous mobility, at least for our kind of vehicles. So even though I'm here complaining and saying we need more projects and things like that, I think one of the positives is there is a lot of support for it. And it is slowly growing. So there's a lot of government grants that are willing to help support the technology. So a lot of support that's slowly getting more traction. I think that's also a positive, and as a community, we just need to make sure that it continues to grow and improve, right? It doesn't lose traction because, again, we're still very early in this technology.

In terms of transportation convenience. So we did a specific study where you can actually call our shuttles to come to your service station. So when it comes to people with disabilities, for example, it's helping them become more independent. What's the reward? I'm looking for more independence, where they can come to a service station where we're programmed to do pickups, and they can use a mobile app to call our vehicle. Our vehicle is then scheduled to go through the route and come and pick them up at a certain location, and then connect them to the local bus station or local train station, and things like that. So in terms of connectivity for people with disabilities, that's been a big emphasis on our end. We've been doing a lot of studies, research, and R&D work with La Trobe University out of Melbourne, Australia, where they essentially developed the app where they could call these vehicles. It will come into the different pick stops, pick up these people, and then drop them off at their location. So, those are success stories that we're really proud of because it's actually improving the life of people who would otherwise be required to order a taxi or would be required to call an Uber or something like that where they're always dependent on somebody else. With the autonomous shuttle, they're no longer dependent on someone else, but they can get around without having to call someone for assistance. So that's been a big plus for those communities as well.

Are you operating all of your vehicles with a safety operator on board?

Globally, a majority of them, especially in the United States, we've had folks ask us not to operate without safety operators. We just want to be cautious. We want to slowly scale that up where we get rid of the safety operator. But we want to take our time in doing that, and we want to make sure we do it as safely as possible. Now, globally, we have had implementations that don't have safety operators.

Are the operators present mostly because people feel safer?

Mostly because people feel safer if there is an operator, the latter, yeah. Guideway, you know that we're programming, think of it as digital tracks on the pathway. It's pretty safe, and it's operating at slower speeds. But I think people are still, it's still early. So we want to make sure they're comfortable without the safety operators before we kind of get rid of them or move them.

But I would say the safety operators on our vehicles have also been designed or trained to focus on other things like customer service as opposed to focusing on driving these shuttles, right? So, you know, it could be to help people. It could be to help them, even though we have what do you call it, ramps and everything. But it's more to be a person there to help with the service, as opposed to driving the vehicle.

Have you seen the AV shuttles affect the other shared mobility options like shared micro-mobility and ride-hailing over time?

We haven't. No, it's really about just making those services more accessible again. Our solution is really designed to connect folks to areas that otherwise don't have other services. So that's where we really focus on, or bringing people from a car park to their airport terminals. So it's just about improving the service, making it more frequent. As opposed to competing with ride-hailing or things like that. We look at ourselves as an extension of that.

What is the latest breakthrough innovation that is expected to improve the AV shuttle operation or has already improved it in the last years?

So one of the things that we've been able to do, we demonstrated that at JFK, and you might be able to see kind of. We've done phase one, and we're about to do phase 2 with JFK early next year. But essentially, what we've been able to do is to develop platooning technologies where we have multiple shuttles, two, three, four, five of them depending on the frequency and how many people we need to move. We're essentially platooning our vehicles. So we can digitally connect them with one another without actually having a connector, but they're digitally connected to each other. And they travel at, say, 25 miles per hour and stay 7 feet apart.
So, why this is important is, think of people going to a stadium. At 1, 1 shuttle might be enough, and in other solutions, we might need 15 of them. So, depending on how many people are needed, we can safely move all of these people quickly pack all of those shuttles, and move them from point A to point B. So that's really been something that we've been excited about, is developing that technology and actually having it work effectively. So I would say that's one that comes to mind.

Are the shuttles also connected with the traffic infrastructure?

So our parent company, HMI Technologies, is heavily involved in road signage and sensor technologies. That's how we initially entered the world of autonomous mobility. To provide some more background, we started by exploring autonomous shuttles for testing with our sensors. However, when we attempted to collaborate with other autonomous vehicle providers, we encountered a common trend where their focus was more on selling a complete vehicle rather than offering a comprehensive solution. In our attempts to work together and create an open-source environment for configuring and integrating our sensors, we often faced resistance. These companies were adamant about keeping their vehicles closed and not allowing any modifications. This limitation hindered our ability to effectively collaborate and integrate our sensor technology. As a result, we decided to take matters into our own hands, leading to the development of OnlyUp in 2016. We formed our own team and built our own autonomous shuttle. Our approach has always been centered around providing a complete solution rather than just selling a vehicle. While we develop some of our own sensors, we also maintain an open-source philosophy, aiming to foster communication and collaboration within the broader ecosystem. That's how we approach our work in the autonomous mobility space.

Have you seen any challenges with trying to connect with the infrastructure?

The challenge we encountered was our struggle to establish effective communication with a couple of traffic lights due to a significant latency issue. Our lidars couldn't reliably detect these traffic lights, which posed a less-than-ideal scenario for our system's design. However, our company had an advantage because we had previously developed our own sensors for road signs. These sensors proved to be invaluable during the implementation process. We were able to address the issue by installing the appropriate sensor technology and updating the traffic lights accordingly. This flexibility allowed us to design and build a comprehensive system from the ground up, ensuring the smooth functioning of our autonomous shuttles. In the various cities where we operate, we frequently encounter outdated sensors and infrastructure that require upgrades to accommodate our technology. In some cases, we take on the responsibility of upgrading these systems at our own cost, or even provide the service for free, to ensure a seamless and safe execution of our autonomous mobility solutions.

When can we expect autonomous shuttles to safely operate at speeds of 15 to 20 miles per hour within mixed traffic?

While the speed itself isn't an issue, we can already operate at speeds ranging from 15 to 20 miles per hour. However, there are several factors to consider before implementing higher speeds in mixed traffic scenarios. From a technological perspective, we have the capability to handle it under specific conditions, but we proceed with caution. When clients express interest in higher speeds, we usually recommend that they establish a specific route or loop, even within mixed traffic. While a dedicated guideway may not always be necessary, we prefer to run a pilot program with them for approximately one to one and a half years to ensure safety and performance. One challenge we face is the potential discrepancy between the promises made and the actual results delivered. This disconnect can lead to disappointment among potential users or customers. Regarding operating at lower speeds like 15 miles per hour on roads with higher speed limits of 25 or 35 miles per hour, there is a challenge in determining where it's safe to operate at a lower speed amid faster traffic. This situation presents a dual challenge, and city authorities often engage in discussions to determine the optimal speed for specific roadways. Our approach involves staying on the far right-hand side of the lane and merging into faster traffic only when necessary. We have successfully implemented this strategy in John Sijong City, Korea. Being part of the conversation and the design process from the project's inception allows us to assess feasibility, inform stakeholders of the possibilities, and align with the project's timeline.