Japan Bilingual Publishing Co.

Transportation Development Research
https://ojs.bilpub.com/index.php/tdr

RESEARCH ARTICLE

Operational and Policy-Related Data Assessment and Recommendations from Review-based Analysis of Autonomous Shuttle Deployments

Dil Samina Diba, B.S. Srinivas S. Pulugurtha*

Department of Civil & Environmental Engineering, The University of North Carolina at Charlotte, 9201 University City Boulevard, Charlotte, NC 28223-0001, USA

ARTICLE INFO

Article history
Received: 14 November 2023
Revised: 18 December 2023
Accepted: 25 December 2023
Published Online: 28 December 2023

Keywords:
Autonomous shuttle
Deployment
Best practice
Operational
Policy

ABSTRACT

The advent of driverless technology and supporting infrastructure has enabled the implementation of autonomous shuttles for enhancing mobility and providing first and last-mile (F & LM) connectivity. These shuttles have been employed to address short-distance travel needs, serve internal transportation needs, and cater to specific use cases, such as recreational parks, business parks, and university campuses. Successful deployment of autonomous shuttles depends on the service location and the target customer base. Factors such as capacity, speed, incidents/crashes, comfort, and road characteristics influence their successful integration into the transportation system. Practitioners can better plan future deployments by learning from past and current autonomous shuttle deployments and their documented outcomes. This study compares the operational and policy-related data from 120 autonomous shuttle deployments worldwide. Additionally, a review-based analysis was conducted to identify the strengths, weaknesses, opportunities, and threats associated with autonomous shuttle deployments. Recommendations for future deployments are made emphasizing the need for longer trial periods and the development of a comprehensive policy framework.

1. Introduction

The public transportation system is an economical and reliable mobility service to the public, particularly for transportation-disadvantaged people. Accessibility is one of the most significant barriers to public transportation in many cities worldwide, especially in areas where fixed-route local bus services are inefficient, and the ridership is unsustainable. For older people, the accessibility of the network system is a significant factor when choosing the mode of travel [1]. Autonomous shuttles are a promising solution to promote mobility, connectivity, and sustainable transportation systems and address future transportation

---

*Corresponding Author:
Srinivas S. Pulugurtha,
Department of Civil & Environmental Engineering, The University of North Carolina at Charlotte, 9201 University City Boulevard, Charlotte, NC 28223-0001, USA;
Email: sspulugurtha@charlotte.edu

DOI: https://doi.org/10.55121/tdr.v2i1.130

demands. They offer a speed advantage over walking and biking, allowing them to expand the transit service area and enhance overall accessibility levels through first- and last-mile (F & LM) connections. They also enable people to travel further by being part of multimodal transportation system [2].

Autonomous shuttles are Level 3 or Level 4 automated vehicles with passenger capacities ranging from 6 to 20. They follow predetermined routes between ~5 to 25 mph, ensuring reliable and efficient transportation. The sensory system of autonomous shuttles is categorized into three parts: navigation and guidance, driving and safety, and vehicle performance [3]. As self-driving electric micro-transit vehicles, these shuttles rely on advanced sensory mechanisms and artificial intelligence (AI) to navigate without human intervention. Different sensors of autonomous shuttles work together to detect and interpret the surroundings efficiently to create safe and compliant routes. Although Level 4 autonomous shuttles are not expected to have traditional manual controls like steering wheels and pedals, a safety operator is still required for safety and security reasons.

Many companies are part of the global market of autonomous shuttles. Navya, EasyMile, Meridian, Olli, and Coast are a few examples [4–7]. Navya stands out with its highest passenger capacity of 15 and a maximum speed of 45 mph. On the other hand, Local Motors' Olli, which was shut down in 2022, is a relatively compact sized shuttle with a passenger capacity of 10 [8]. The autonomous shuttles are equipped with advanced onboard technologies, such as cameras, Light Detection and Ranging (LiDAR), a global positioning system (GPS), and sensors for navigation and safety purposes. Battery capacity and charge times also vary among the models. While Navya has the largest battery capacity at 33.0 kWh, Easymile's capacity is 20.0 kWh. The Boston-based company, "Optimus Ride", is another company that has autonomous shuttles. Baidu is a dominant company that is primarily doing business in China. The autonomous shuttles are designed to operate without a human driver and have different features and capabilities. Transdev, Keolis, Free2move, Beep, Oceaneering, etc., are working as operators of autonomous shuttles. Toyota also has its minibus shuttle. The buses are aimed at the carbon-neutral future of the automaker's mobility services [9].

Four stakeholder organizations, a public organization, a partner organization, a shuttle manufacturer, and a private operator, are involved in autonomous shuttle deployments [10]. Public organizations are mainly the ones who look after the legal process and permissions. The transportation departments of cities, states, and transit agencies are part of this group. Partner organizations create the whole plan for deploying shuttles with specific objectives. This group mainly includes universities, research organizations, and different communities. Shuttle manufacturers are dealers of the rigid body of shuttles. Private operators are primarily responsible for the shuttle operation, software and data collection.

Countries like Australia, Switzerland, France, and the United States of America (USA) have embraced the deployment of autonomous shuttles, paving the way for a paradigm shift in urban mobility [10]. The use of autonomous shuttles is expected to be more in busier areas. For example, a study found that though autonomous shuttle trips were distributed across the county, the downtown area experienced more trips [11].

Despite the widespread utilization of autonomous shuttles in diverse environments such as public roads, closed communities, campuses, parking areas, and airports in numerous countries, a notable research gap exists regarding a comprehensive global and national comparison. Previous studies have primarily concentrated on a limited number of pilot cases. A holistic assessment of the aggregated learning from many such deployments is unreported. There is a critical need to gather data, compare, assess and adopt a broader perspective encompassing domestic and international deployments. A detailed assessment of past and current deployments would enable practitioners to gain valuable insights to make well-informed policy decisions that align with the specific requirements of each context.

This study explores the transformative potential of autonomous shuttles in revolutionizing public transportation. Through an in-depth analysis of 120 pilot shuttle deployments worldwide, this research delves into autonomous shuttle specifications, lessons learned from past and current deployments, and the challenges faced during these deployments. This study seeks to formulate a robust policy framework for the future of autonomous shuttle initiatives by synthesizing operational and policy-related data and by conducting a comprehensive review-based analysis to identify the strengths, weaknesses, opportunities, and threats associated with autonomous shuttle deployments. Through this extensive investigation, the study aims to address the following key questions.

- What is the current state of autonomous shuttle deployments worldwide?
- What are the potential challenges for future pilots and permanent deployments of autonomous shuttles?
- What are the implications of learnings from past and current autonomous shuttle deployments for shaping the future of transportation systems?

2. Research Design and Methodology

As the first step, an extensive exploration of electronic research databases, such as Google Scholar, Web of Science, and ScienceDirect was conducted to gather information on past and current autonomous shuttle deployments. Various search terms, including “autonomous shuttle”, “automated bus”, “driverless shuttle”, and “self-driving shuttle”, were utilized to identify pertinent articles and academic literature on the subject. Additionally, complimentary searches were conducted, combining terms like “mobility on demand”, “user experience”, and “intention to use” with “autonomous shuttle”.

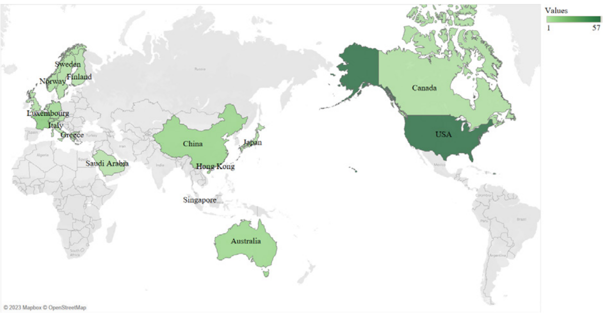
Literature encompassing government or industry reports, non-academic research, and editorial papers were also reviewed. Furthermore, articles from magazines and newspapers were reviewed to gain insights into specific incidents of autonomous shuttle deployments. By drawing information from these diverse and reliable data sources, a comprehensive understanding of the current landscape and operational aspects of autonomous shuttles across different regions was achieved.

The study encompassed two types of analysis. The first type involved conducting a descriptive analysis of past and current deployments worldwide. Where appropriate, data for autonomous shuttle deployments within the USA were also presented separately. The key focus areas were safety, operational efficiency, economic implications, and policy considerations. In the second part, the findings and challenges encountered in past and current autonomous shuttle deployments were studied. A comprehensive review-based analysis was performed to provide a holistic view. Finally, the implications derived from the investigations and potential areas for future research are summarized.

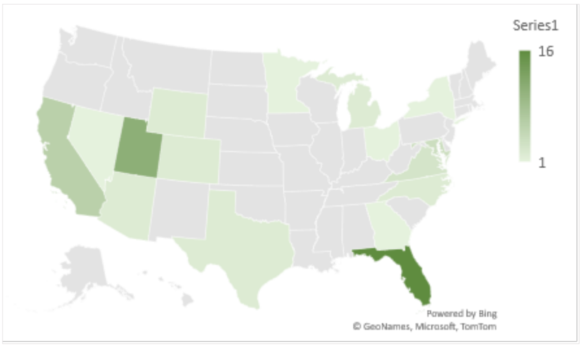
3. Autonomous Shuttle Deployments Summary

One-hundred-and-twenty autonomous shuttle deployments from 21 countries were identified for the comprehensive analysis; 52.5% are from the USA and 47.5% of them are from 20 other countries [12]. When examining data from 21 different countries, the term “worldwide” is utilized when the analysis encompasses data from all 21 countries. Conversely, the term “other countries” is employed when the analysis excludes data from the USA. The intent is to offer a visual presentation illustrating the current status of autonomous shuttle deployments worldwide, including within the USA.

Figure 1a shows the identified deployments all over the world. For this research, 57 deployments from the USA, 13 deployments from France, 8 deployments from China, 7 deployments from Australia, 5 deployments each from Germany and Switzerland, 3 deployments each from Canada and Norway, 2 deployments each from Austria, Japan, Luxemburg, Sweden, UAE, and the UK and 1 deployment each from Finland, Greece, Hongkong, Italy, Netherland, Saudi Arabia, and Singapore were identified.



(a) Worldwide deployment of autonomous shuttles

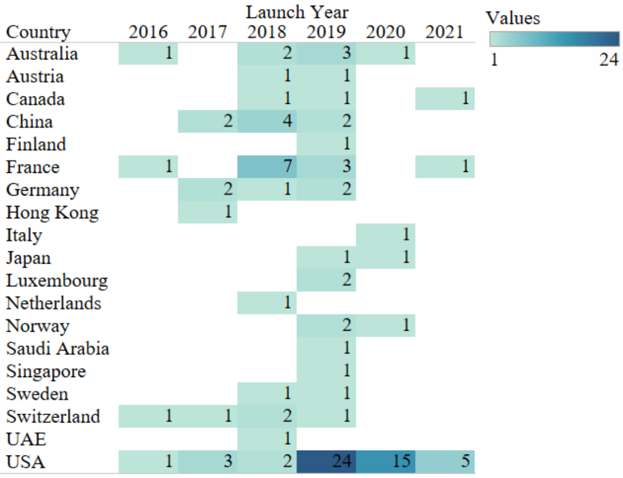


(b) Deployment of autonomous shuttles within the USA

Figure 1. Identified autonomous shuttle deployments.

Per the National Highway Traffic Safety Administration (NHTSA), autonomous shuttles can be deployed for a specific time on a fixed route with some regulations. The United States Department of Transportation (USDOT) is trying to increase the successful deployment of relevant projects, ensure the efficient use of public funds, improve awareness and consideration of universal design and accessibility, and inform engagement in this area. The University of Michigan first launched the autonomous shuttle pilot project in February 2016 [13]. Since then, autonomous shuttles have been deployed in various places with different trial periods in the USA. Figure 1b shows the identified deployments in different states of the USA. Sixteen autonomous shuttle deployments were observed in Florida, while 11 autonomous shuttle deployments were observed in Utah.

Figure 2 shows the autonomous shuttle deployments worldwide by year. Autonomous shuttle pilot deployments commenced in 2016 across several countries, including Australia, Switzerland, France, and the USA. The year 2019 witnessed the highest number (24) of these deployments. However, the number of deployments experienced a decline in 2020, attributed, at least in part, to the impact of the COVID-19 pandemic on the autonomous shuttle industry.



Country	2016	2017	2018	2019	2020	2021
			Launch Year			
Australia	1		2	3	1	
Austria			1	1		
Canada			1	1		1
China		2	4	2		
Finland				1		
France	1		7	3		1
Germany		2	1	2		
Hong Kong		1				
Italy					1	
Japan				1	1	
Luxembourg				2		
Netherlands			1			
Norway				2	1	
Saudi Arabia				1		
Singapore				1		
Sweden			1	1		
Switzerland	1	1	2	1		
UAE			1			
USA	1	3	2	24	15	5

Figure 2. Autonomous shuttle deployments by year.

3.1 Comparison of Operational Data

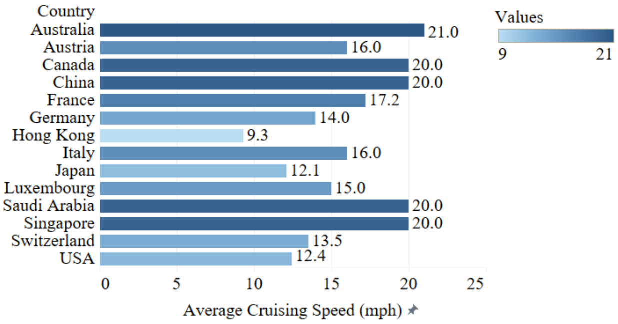
The operational characteristics of autonomous shuttles differ significantly from traditional public transportation systems, primarily due to their status as autonomous micro-transit. Various factors such as cruising speed, track length, number of stops per mile, and vehicle density per mile were analyzed and compared among different autonomous shuttle deployments. These metrics play a crucial role in understanding and evaluating the operational aspects of these innovative transportation solutions.

Average Cruising Speed

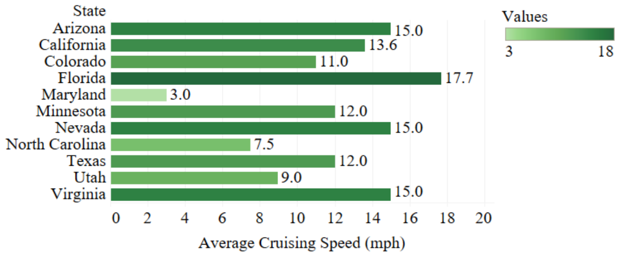
Autonomous shuttles are slow-speed autonomous micro-transit vehicles with maximum speeds ranging from 25 to 27 mph. However, it is observed that the cruising speed can range from 3 mph to 25 mph across 63 recorded deployments worldwide. Figure 3a provides insights into the average cruising speeds of autonomous shuttle deployments, showcasing variations in the operational speeds of autonomous shuttles across the deployments.

Australia has the highest average cruising speed (21 mph), and Hong Kong has the lowest cruising speed (9.3 mph). The variation in the cruising speed could be attributed to the track length, road geometry, traffic flow, and other infrastructure-related characteristics. For example, the cruising speed would be lesser if autonomous shuttles were deployed on public roads. This could be due to continuous interactions with other vehicles, pedestrians, and the presence of intersections.

Figure 3b shows the average cruising speed for different states in the USA. The highest average cruising speed is 17.7 mph in Florida, whereas the lowest average cruising speed is 3.0 mph in Maryland. For the USA, the average cruising speed is 12.42 mph.



(a) Worldwide



(b) USA

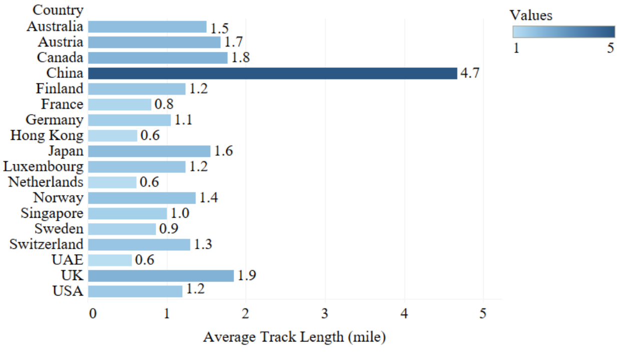
Figure 3. Average cruising speed.

Average Track Length

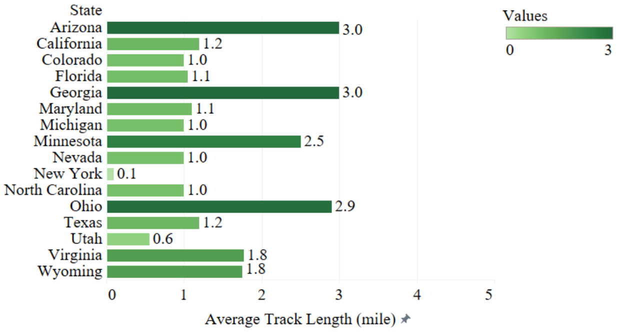
The design of autonomous shuttles predominantly focuses on facilitating short route travel paths, particularly for F & LM connectivity. These shuttles are optimized for low speeds and serve as connectors between public transportation systems or parking facilities. Figure 4a showcases the average track length of identified autonomous shuttle deployments, highlighting their suitability for short-distance transportation.

In China, the highest track length for autonomous shuttles is 4.67 miles. In comparison, the overall average track length for 82 other deployments stands at 1.35 miles. If the deployments in the USA are excluded, the average track length for autonomous shuttle deployments is 1.54 miles in other countries.

Figure 4b provides a visual representation of the average track length in different states of the USA. Within the USA, track lengths have been measured for 35 deployments. Among these, the autonomous shuttle deployment in Virginia had the highest recorded track length (3.5 miles). On the other hand, the lowest track length recorded is a mere 0.07 miles in Minnesota, indicating a comparatively shorter route for autonomous shuttle operations in that particular case [14]. The average track length of autonomous shuttle deployments within the USA is about 1.1 miles.



(a) Worldwide

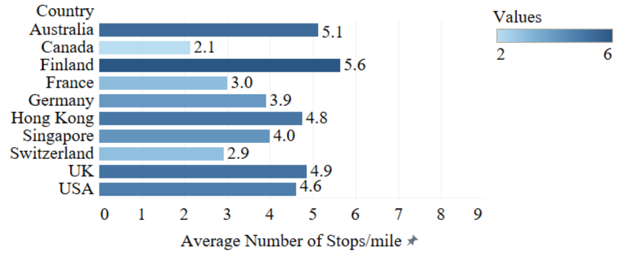


(b) USA

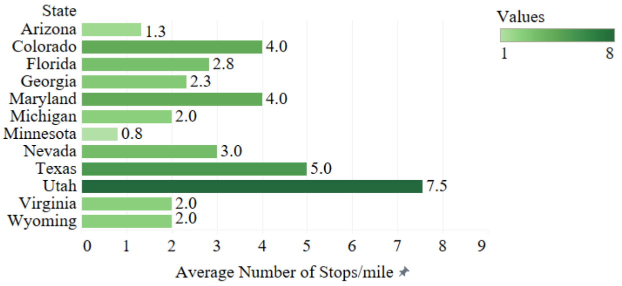
Figure 4. Average track length.

Average Number of Stops per Mile

Figure 5a provides an overview of the average number of stops per mile for identified autonomous shuttle deployments, shedding further light on the distribution of stops in these deployments.



(a) Worldwide



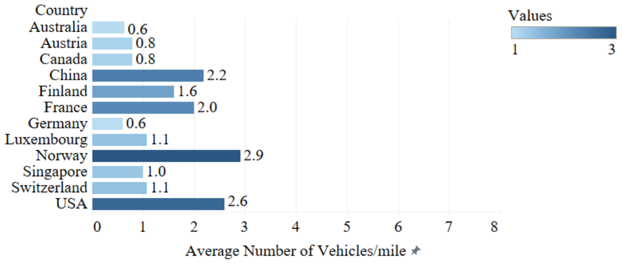
(b) USA

Figure 5. Average number of stops per mile.

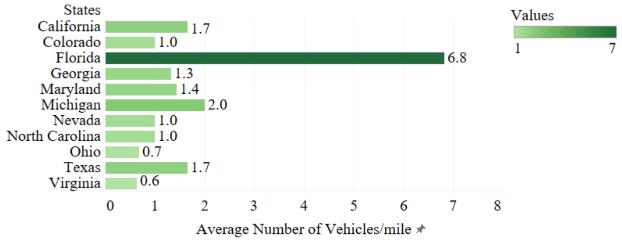
Approximately 60% of the identified autonomous shuttle deployments have 2 or 3 stops. However, there are exceptions to this trend. One autonomous shuttle deployment in Australia had 36 stops (5.12 stops per mile), while another one in the UK had nine stops (4.86 stops per mile) [15,16]. Of the 33 autonomous shuttle deployments with recorded stop numbers in the USA (Figure 5b), 13 deployments had only two stops. Within the USA, one autonomous shuttle deployment in Florida and Georgia had the highest number (7) of stops.

Average Number of Vehicles Per Mile

The average number of vehicles per mile is a key performance indicator in autonomous shuttle pilot deployments' overall decision-making. The number of vehicles was available for 88 out of the identified 120 autonomous shuttle deployments. In 63 of these deployments, both the number of vehicles and track length data were identified. Out of these, 34 deployments had a track length equal to or greater than one mile. An analysis of the average number of vehicles per mile was carried out for these 34 deployments. Figure 6a presents the average number of vehicles per mile for the identified autonomous shuttle deployments worldwide, providing valuable insights into the fleet size.



(a) Worldwide



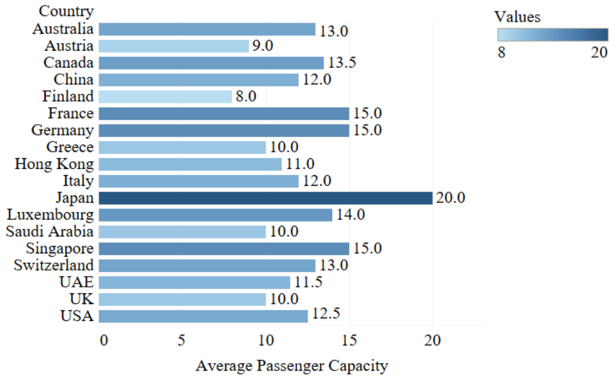
(b) USA

Figure 6. Average number of vehicles/mile.

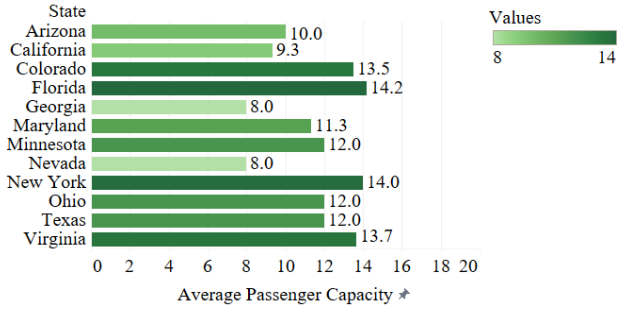
In China, the maximum number of vehicles used in the deployment was 22 in 2019. In general, only one vehicle was used in 47% of the autonomous shuttle deployments, while two vehicles were used in 33% of the autonomous shuttle deployments. Figure 6b shows the average number of vehicles per mile used in each deployment in the USA. The highest number of autonomous shuttles used in a deployment was 8 in Florida. Hence, the average number of vehicles/mile is highest in Florida. The average number of autonomous shuttles used in deployments is 3 in the USA.

Average Passenger Capacity

Figure 7a provides an overview of the average passenger capacity of autonomous shuttle deployments worldwide, highlighting the variations in passenger capacity across different regions. According to the design specifications, the passenger capacity of an autonomous shuttle can range from 6 to 20 people per vehicle. However, the average passenger capacity is approximately 13 people per vehicle based on data from 65 recorded deployments worldwide. Notably, many deployments reduced the number of passengers riding the shuttle during the COVID-19 pandemic by half for safety reasons.



(a) Worldwide



(b) USA

Figure 7. Average passenger capacity.

The maximum passenger capacity was 20 people per vehicle in an autonomous shuttle deployment in Japan. Finland had the lowest average passenger capacity (8 people/vehicle). Figure 7b shows the average passenger capacity of autonomous shuttles for different states of the USA. The highest average passenger capacity is in Florida.

3.2 Comparison of Policy-related Data

Policy-related data includes the riding fee structure and the specific environment or land use where the autonomous shuttles were deployed. Furthermore, in the latter part of this section, the operational data is examined and compared accounting for the diverse environments in which the autonomous shuttles operate.

Riding Fee

The majority of autonomous shuttle rides were provided free of charge, with some instances where a small fee was imposed to observe passenger behavior [17]. In the USA, no paid services were reported, and the distribution of selected pilot deployments is as follows: 84% offered free rides, 2% are free for residents, 7% operated on an on-demand basis, and 7% required pre-registration for shuttle usage [12]. As per the selected pilot deployment of other countries, approximately 90% of deployments offered free rides to passengers, while 2% operated on an on-demand basis, 4% required payment for the service, and another 4% necessitated pre-registration to use the autonomous shuttle.

Environments of Routes

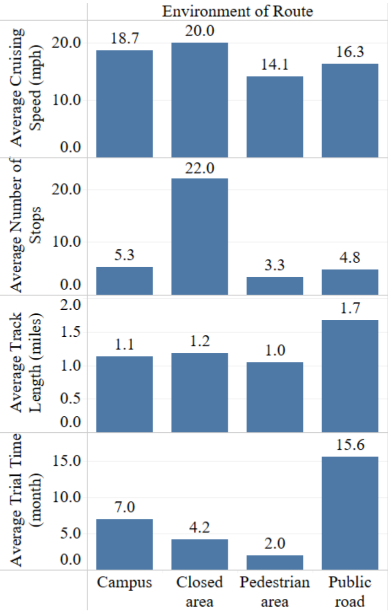
The environment of the identified autonomous shuttle deployments are classified into four groups- campus, closed area, pedestrian area, and public road. The campus is defined as routes with limited interactions with other modes of transportation, not a public road, i.e., college campus, office park, or stadium. The closed area is mainly routes inside a closed community, where the autonomous shuttle hardly interacts with other vehicles. The pedestrian area is defined as low-speed routes where frequent autonomous shuttle-pedestrian interaction is possible. The public road is mainly open, where the autonomous shuttle interacts frequently with other vehicles.

Across different countries, the deployment of autonomous shuttles varied in terms of their locations. From the selected pilot deployments, in 20 other countries excluding the USA, 68% of these deployments are on public roads, 14% are in pedestrian areas, 5% operate within closed areas, and 13% are deployed on various campuses, such as universities or corporate premises. In the USA, the distribution is slightly different, with 42% of deployments on public roads, 5% in pedestrian areas, 26% in closed areas, and 27% serving campuses. These distributions reflect the target customer base and the diverse strategies adopted in different regions for integrating autonomous shuttles into their transportation systems.

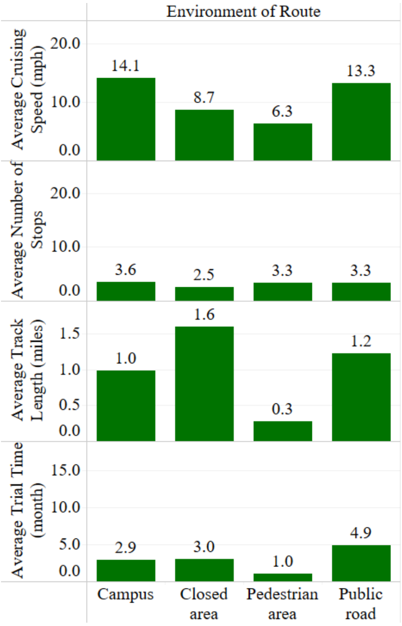
The geographical location of an autonomous shuttle deployment significantly influences the operational environment. Autonomous shuttle deployments may be relatively more feasible and practical in countries where many public roads are characterized by slower speeds and narrower dimensions. The design and capabilities of autonomous shuttles are well-suited to navigate and operate effectively on these types of roads, making them a practical choice for transportation solutions in such environments.

3.3 Comparison in Terms of the Environment of Autonomous Shuttle Deployments

The operational characteristics of the autonomous shuttle deployment vary with the type of environment. Figure 8 shows the average cruising speed, the number of stops, track length, and trial time for road environments in other countries and the USA.



(Other countries)



(USA)

Figure 8. Characteristics by the route environment.

Several comparisons can be drawn regarding different aspects of autonomous shuttle deployments from Figure 8. In other countries, the average cruising speed is highest in closed areas. At the same time, the highest average cruising speed is on campuses in the USA. For pedestrian areas, the cruising speed is lower than the other areas for both the USA and other countries. As expected, the cruising speed is lower in areas with higher interaction between autonomous shuttles and pedestrians. Moreover, the USA has the lowest average cruising speed in pedestrian areas. However, the speed in other countries is more than double that of the USA. The average number of stops is highest in closed areas for other countries, driven by an Australian deployment with 36 stops. However, the average number of stops in the USA does not significantly vary based on the route environment. Other countries exhibit the highest average track length on public roads. At the same time, the USA shows the highest average track length is in closed areas, with public roads being the second highest. Additionally, public roads have a longer average trial time in both cases. However, for other countries, the trial time on public roads is more than three times higher compared to the USA.

4. Learnings and Challenges

Autonomous shuttles are different from long-route buses in capacity and route length. The purpose of the autonomous shuttles is to supplement the long route transit, mainly from the F & LM connectivity perspective. The main motto of these deployments is to test the technology under real-world scenarios and develop them accordingly [18]. As this is a new technology, many challenges await in line before permanent deployment.

Autonomous shuttles can (i) provide service from predetermined bus stops to public transportation routes for daily commuters (regular or on-demand), (ii) provide service to a particular center for tourists (during daytime), and (iii) deliver goods and services [18]. Primarily the deployment offers three main functions: fleet management, system monitoring, and customer experience [19]. The previous section presents a macroscopic analysis of the operation-related and policy-related data for the identified autonomous shuttle deployments. In this section, a microscopic analysis is conducted by examining the autonomous shuttle deployments in eight different domains. They are (a) vehicle performance, (b) safety and security, (c) traffic management, (d) weather condition, (e) infrastructure, (f) social justice and equity, (g) legal considerations, and (h) user acceptance. The learnings from the autonomous shuttle deployments are discussed next.

4.1 Vehicle Performance

In New South Wales, Australia, an autonomous shuttle was deployed in three phases to check the performance of this new addition in different scenarios. BusBot went through trials starting with a nine-week trial at a high-profile and controlled environment for residents and tourists. The second phase at the Toormina Marian Grove Retirement Village in 2019 was a home for 68 to 98-year-olds. This trial provided a valuable test case to understand the mobility needs of an older community. In the third phase at the North Coast Regional Botanic Garden through the beginning of 2020, an autonomous shuttle was deployed in a closed public place [17].

One frequently recorded issue was that the shuttle would halt even if no detectable obstacles were on the road. In the case of Austria, the anticipated reason for such incidents could be roadside branches or bushes and unreliable network data transfer, which led to improper signal transmission [18]. Another issue was blind spot detection, which can be prevented with the correct positioning of 360-degree LiDAR sensors [18]. The sensors detect objects in the front or the back of the shuttle. Any object moving over ~18.6 mph cannot be reliably detected. However, this can be improved using higher resolution LiDAR sensors or some extra sensor installation [18].

All autonomous shuttles in the identified deployments are mainly Society of Automotive Engineers (SAE) International defined Level 3 and Level 4 automated vehicles. These shuttles can maneuver on pre-defined simple routes. However, the designed autonomous shuttles can still not cope with the complicated public route, and the operator needs to act to pass any obstacle or turn left [18].

An additional challenge encountered with autonomous shuttles pertains to their battery life. For example, in the case of Utah 1950 West deployment, service had to be curtailed at 5:30 p.m. instead of the intended 6:00 p.m. due to a battery power shortage [19]. The operation of autonomous shuttles is impacted by cold weather conditions, resulting in prolonged charging times. Colder temperatures cause a significant drop in the battery core temperature, negatively affecting the shuttle's operations. The charging process also takes longer in cold weather than in warmer temperatures [17]. This highlights the importance of battery capacity and management in ensuring uninterrupted service and meeting the operational requirements of autonomous shuttle deployments.

The operational capabilities of some autonomous shuttles seem to be limited to specific weather conditions. They are designed to operate under certain weather parameters, including the absence of heavy or medium snowfall, no water accumulation or flow on the ground, no snowy or frozen road conditions, no heavy rains or storms, humidity levels below 95%, and stabilized wind speeds below 31.1 mph (with peak speeds below 40.4 mph [5]. Additionally, the vehicle requires a clear track without dust, fog, or vapor. These weather conditions are essential for ensuring the safe and reliable operation of some autonomous shuttles [5]. Understanding and operating per these limitations is critical until technological advancements help address the problem.

4.2 Safety and Security

Drivers of any conventional vehicle must maintain uninterrupted control over the vehicle and adapt the speed as per the speed limit requirement. However, the operator need not have direct control over the steering wheel in Level 4 autonomous shuttles. For safety purposes, an operator is always present in the autonomous shuttle who can manually operate the vehicle when in need. Training of the safety operator includes familiarity with the technical specifications of the shuttle, manual control of the shuttle, autonomous driving procedure, monitoring and reporting, and management of emergencies [18].

One of the biggest challenges for autonomous shuttles is interacting with the road user on public roads [18]. For increasing safety, additional acoustic signals and visual indicators are employed in some of the shuttles [18]. In Japan, a visually impaired athlete got injured by an autonomous shuttle while crossing the road [18]. On July 18, 2019, a minor crash occurred in Wien, Austria. A pedestrian did not see the ~7.5 mph autonomous shuttle approaching her. The shuttle's reaction time was 1.6 seconds, exactly how it should be [20]. If the shuttle stops by any obstacle, it shows visual information [18]. However, pedestrians were not used to the new technology. Furthermore, there is no scientific evidence or rules on what signalizations will lead to what behavior of road users [18].

4.3 Traffic Management

Autonomous shuttles can improve public transportation through F & LM connectivity [18]. However, people prefer private vehicles if the distance is too far [18]. Some deployments tried to reduce the number of vehicles on busy roads to reduce congestion. In Sweden, the parking fee near an autonomous shuttle station was reduced by half so that people could park their vehicles and take the shuttle [21].

According to legal regulations, autonomous shuttles are limited to a maximum speed of 12.4 mph [18]. However, to make a left turn without stopping, the shuttle must have a visibility clearance of 150 to 200 feet [22]. As a slow-moving vehicle, an autonomous shuttle performs better with a dedicated lane [23]. In response to its inability to recognize colors, modifications to traffic signals are required and have been implemented at some locations [22].

4.4 Weather Conditions

Autonomous technology is sensor-based and camera-based. Therefore, autonomous shuttles cannot move in heavy snow or rainfall. The dust can stop autonomous shuttles from the gravel's reaction with the sensors [23]. In the case of the Calgary Zoo, the autonomous shuttle slowed down while snowing, but once the snow stopped, the autonomous shuttle resumed at normal speed [23]. Light rain did not affect the movement of the autonomous shuttle, and the vehicle operated perfectly with snow on the ground. However, the vehicle stopped when it drove into a puddle [23].

With the current technology, autonomous shuttles cannot run in extreme weather conditions. Especially the technology should be tested to check how it operates during heavy snowfall, rain, sleet, and smoky conditions [23]. Also, the ventilation system or air-drying system was insufficient to prevent windscreen in the case of damp weather. As a result, the onboard operator could not see the road from inside.

Autonomous shuttles operated well, maintaining a safe distance from other vehicles, pedestrians, and obstructions on the track under dry pavement conditions with no precipitation [17]. According to the City of Calgary report, the sensor must be improved to handle all weather conditions before it can be operated without any safety operator [23].

4.5 Infrastructure

A solid infrastructure with a good network is essential for the safe and smooth operation of autonomous shuttles. They best fit paved environments with well-maintained roadways [23]. Road furniture was installed for LiDAR sensors to correctly map out the Candiac area [22]. In the rural area of Koppl, the pilot project was not so prompt due to the limited ability of LiDAR sensors, GPS, poor road infrastructure with irregulated intersections, and high elevation [18]. In Calgary Zoo, a portable ramp was brought as the roadway gravel impacted the existing ramp [23]. The road functional class is also an important factor for route selection. Installing localization infrastructure was necessary due to the rural nature of one site [21].

Different kinds of modifications were required in almost all the examined deployments. The deployment of Candiac needed to install a stop sign to allow the shuttle to make a left turn [22]. If the route is not circular, the autonomous shuttle needs some extra path for a U-turn. The municipality of Koppl constructed a side road at the end of the route for turning the shuttle [18]. For safety reasons, a dry garage is required for the shuttle to store and charge in need. In the hillside area of Koppl, an overlooking place was needed for correct signal passing between the base station and the shuttle [18].

4.6 Social Justice and Equity

The micro-transit system improves the quality of the public transportation system, especially in the rural area. Autonomous shuttles encourage people to use the public transportation system with F & LM connectivity as one of the primary objectives [22]. In 2018, fleets of autonomous minibuses were used for full-scale demonstrations in low to medium-demand areas of four European cities [24]. However, the expense was observed to be too high to run a micro-transit, which could be a major reason for the unpopularity of micro-transit systems on public roads [18].

In the case of Austria, the municipality of Koppl presumes that autonomous shuttles can fill the gaps of infrequent bus links in the village area [18]. The National Federation for the Blind indicated that this technology has much potential for increased mobility of disabled passengers [25]. However, commuters registering for autonomous shuttles may experience a lack of next/previous vehicles after midnight. Hence, it may increase the travel time during night hours [11].

Autonomous shuttles on public roads were aimed at becoming an enduring, long-lasting service for the city [26]. Parking is always a problem in the entertainment area or busy downtown. Some deployments were in busy downtown areas with a vision to solve this issue [21].

In Peoria, the elderly community was served by RoboRide and RoboRide Medical [25,27]. Although this new technology came with the vision of a slow-moving safe transit motto, shuttles would be better at high speed and on long routes [23]. There is a chance of potential loss of driving jobs with autonomous technology in transportation systems [23]. However, with Level 4 autonomous vehicles, an operator on board must be in the vehicle. Therefore, the potential loss of driving jobs may not be severe until autonomous shuttles are fully automated (Level 5).

4.7 Legal Considerations

Currently, there are no instances of permanent deployment of autonomous shuttles worldwide. Consequently, policies and regular costs associated with autonomous shuttle deployment remain uncertain. For an autonomous shuttle operating at SAE International Level 3 and higher, a driver or operator's continuous oversight of the road or traffic situation is not required [28]. However, legal requirements are crucial in facilitating shuttle deployments on public roads. One primary requirement is the definition of stakeholder roles. Additionally, obtaining a test license plate for public road testing is necessary for autonomous shuttle deployments. In Austria, a shuttle deployment included vehicle liability insurance coverage of 20 million Euros [18]. These legal considerations and insurance provisions are vital aspects that must be addressed for the successful and regulated operation of autonomous shuttles on public roads.

4.8 User Acceptance

User acceptance is highly crucial for F & LM connectivity. The user experience survey from the pilot program of Calgary Zoo shows that people are comfortable with the autonomous shuttle on a separate right-of-way [23]. People will prefer to take a car if the distance from home is very far, but they may prefer to walk if it is too short [18]. With the deployments on public roads, people realized that driverless vehicles are no longer a futuristic dream.

Autonomous shuttles perform best when not interacting with other motor vehicles [23]. However, passengers realized that regular service would not be available too soon with the current technology and present infrastructure. A survey from Austria asked the riders if they could imagine autonomous shuttle service as a replacement for private cars, and only 39.9% responded positively [18]. According to the survey report of Calgary Zoo, 39% of the respondents were comfortable with the autonomous shuttle on normal roadways, and 25% of the respondents were comfortable using the autonomous shuttle on the freeway [23]. With the Estonian shuttle, a passenger survey showed that people are ready to accept the technology with its safety and comfort [6]. Similarly, 90% of passengers were satisfied with the autonomous shuttle service, and 69% found the autonomous shuttle valuable and effective in Sweden [21]. About 80% of users in Switzerland were positive about autonomous shuttle safety [22].

According to survey findings from Utah, most respondents (94%) expressed a sense of safety while utilizing the autonomous shuttle service [19]. Furthermore, a notable proportion (14%) utilized the shuttle to connect with prevailing transit options, demonstrating its effectiveness in facilitating seamless multimodal transportation. The suitability of autonomous shuttles for catering to the transportation needs of the elderly community was exemplified in Florida, specifically in the case of Move Nona, where customers with wheelchairs required assistance during their autonomous shuttle commutes [23].

Most of the past and current autonomous shuttle deployments are for a short time. Therefore, the passenger surveys reflect the initial excitement scenario [22]. Long-term experiences may differ from initial perceptions. Giving a unique name to any shuttle seemed to help people get more thrilled and familiar with the autonomous shuttle [23]. For example, 72% of the respondents came to Calgary to experience the shuttle ride only [23].

4.9 Review-based Analysis to Identify Strengths, Weaknesses, Opportunities, and Threats

The rapid advancements in autonomous vehicle technology have brought about significant changes in transportation. Among these innovations, autonomous shuttles have emerged as a promising solution to address transportation challenges and improve mobility in various urban and suburban settings. Autonomous shuttles have the potential to revolutionize public transportation by filling the gaps in existing transit systems and providing seamless F & LM connectivity. As with any new technology, autonomous shuttles come with their own set of challenges. Understanding these factors is crucial to assess the feasibility and effectiveness of deploying autonomous shuttles in real-world scenarios.

By conducting a review-based analysis, this study aims to gain valuable insights into the benefits and challenges of incorporating this cutting-edge technology into transportation networks. Through a comprehensive evaluation of these factors, stakeholders can make informed decisions, devise effective strategies, and overcome obstacles to ensure the successful integration of autonomous shuttles in the future of public transportation. Table 1 summarizes findings from analysis based on the literature review.

Table 1. Review-based analysis—summary.

Strength	Weakness
• The autonomous shuttle is mainly designed to supplement the prevailing transit system by closing gaps in transportation services (F & LM connectivity) [6]. • As the autonomous shuttle will contribute to F & LM connectivity, it may increase the number of public transportation passengers. • As there is an accessibility ramp on the autonomous shuttle, it will allow elderly and disabled people to commute independently. Hence, an increase in the mobility of disabled passengers can be expected [1]. • Autonomous shuttles could reduce the travel time and delay of public transportation system users. • Mayo Clinic used autonomous shuttles for collecting COVID samples for tests. Hence, autonomous shuttles can be helpful in emergencies [29]. • Autonomous shuttles can efficiently deliver goods and services within short routes. • The average operational hours of an autonomous shuttle range from 10 to 12 hours. Consequently, as the use of autonomous shuttles increases, gas trips could be reduced due to increased reliance on public transportation. With fewer gas trips, emissions are expected to be less as well.	• Autonomous shuttles are slow-moving Level 3 and Level 4 autonomous vehicles [6]. Hence, low speed can be a concern for other road users. • In mixed traffic, without an exclusive lane, the operation of autonomous shuttles may affect other vehicles' travel time and delay. • The main purpose of an autonomous shuttle is to supplement public transportation. Hence, the target customer base could be only those commuting using public transportation systems. • In the USA, public transportation systems are often not fully utilized, raising the possibility of underutilizing autonomous shuttles. • After midnight, users of autonomous shuttles may experience a lack of next/previous vehicle to complete their trip [15]. • Autonomous shuttles are still in the testing period. Hence, the license and data security policies are not clear yet. • Autonomous shuttles cannot change lanes automatically, which can be a barrier for travelers. • Users are less willing to commute autonomous shuttles with fees [30]. • The passenger capacity of an autonomous shuttle is 8 to 15, limiting its applicability to lower travel demand scenarios. • Demand-supply analysis from real-time data is not possible yet due to the pandemic. • The autonomous shuttle cannot operate in bad weather.
Opportunities	**Threats**
• In the long run, autonomous shuttle service can increase the use of public transportation and decrease the number of personal vehicle trips. • It could be a solution for improving the viability of low-ridership corridors and areas that cannot support the high cost of fixed-route service. • It could be a perfect addition to the autonomous future and for enhancing "equity". • Successfully deploying the autonomous shuttle and autonomous bus may help complete the travel trip chain for many transportation-disadvantaged people.	• In the long run, this technology can reduce the minimum physical activity of adults. • One of the most challenging aspects is the uncertain reasons for stops and incidents. • Uncertainty concerning public acceptance and adoption of autonomous shuttles could be a barrier.

5. Implications

5.1 Industry and Managerial Implications

From the review of all the shuttles, it is evident that upgrading the sensors of autonomous shuttles is essential to improve object detection and reduce false detections that lead to sudden stops. This can be achieved by revising the position of LiDAR sensors to enhance blind spot detection. Additionally, industry experts and practitioners should focus on improving the battery life to mitigate the impact of weather conditions on the autonomous shuttle's performance. Manufacturers and operators should prioritize technological advancements to enhance vehicles' overall performance and safety. Operator training is also crucial to ensure the competency and aptly handling of the autonomous shuttle during its operation.

5.2 Policy-level Implications

A noteworthy limitation of the current design is that the autonomous shuttle cannot change lanes. Practitioners should carefully choose the deployment areas, considering this constraint. Moreover, deploying the shuttles in mixed-traffic areas to observe their performance in complex environments is essential. To enhance road user awareness, practitioners should inform them before the autonomous shuttle's presence on the road, as unfamiliarity can lead to uncertain interactions with the vehicle. Offering reduced parking fees can be an effective technique to incentivize users to ride autonomous shuttles, increasing their willingness to adopt this mode of transportation.

Necessary changes must be made to the infrastructure. It is crucial to check the LiDAR sensor requirements to map out the autonomous shuttle's operating area. Moreover, ensuring the availability of dry garage space is essential to protect the autonomous shuttles from adverse weather conditions and ensure their readiness for operation. Establishing a comprehensive legal framework is a priority as it will facilitate a smoother and more regulated integration of autonomous shuttles into the transportation ecosystem.

Practitioners must prioritize safety, technological advancements, public awareness, and social and legal considerations to unlock the full potential of autonomous shuttles in transforming transportation and urban mobility. Collaborative efforts among stakeholders are crucial to overcoming challenges and ensuring that autonomous shuttles become a reliable, efficient, and equitable mode of transportation.

5.3 Future Research Implications

The prospects for autonomous vehicles in the transportation industry are promising, with technology showing readiness in examined cases. However, achieving fully driverless transportation and adapting to mixed traffic conditions presents a lengthy and challenging journey. To ensure successful deployment, aligning technology improvements with infrastructure, connectivity, safety, regulations, and human factors is crucial. Analyzing the perceptions of practitioners and industry experts will provide insights into areas for improvement and make the autonomous shuttle more appealing and powerful. Although users have a positive attitude towards autonomous shuttles, understanding transportation system users' willingness to adopt and pay for autonomous shuttles is vital. Further research on advancements in vehicle technology, infrastructure enhancements, and public acceptance is essential for the widespread and successful deployment of autonomous shuttles.

6. Conclusions

Autonomous shuttles as automated micro-transit can have significant implications in enhancing accessibility and usage of public transportation systems. This study summarizes past and current autonomous shuttle deployments regarding their operational and policy-related aspects. Moreover, learnings from past and current deployments are also presented by examining eight domains. The study highlights operational and policy-related characteristics, emphasizing a research gap in comparing deployments worldwide.

Variations in operational metrics and the impact of environmental factors, weather, infrastructure, and user acceptance were identified. The review-based analysis indicates that autonomous shuttles can supplement public transportation systems, but improvements are needed prior to large-scale permanent deployments. The synthesis, with its insights, can be helpful to stakeholders.

The long-term goal of achieving completely driverless autonomous shuttles without onboard operators is a significant aim for specific deployments [31]. However, urban planners and transportation managers are poised to face numerous challenges in the coming years as they work to provide travel options that support autonomous vehicles, encompassing economic, technological, institutional, and societal hurdles [16]. While autonomous shuttles are still in the research and development stage, it is evident that further progress is required before large-scale permanent deployments become a reality [18].

Conflict of Interest

All authors certify that they have no affiliations with or involvement in any organization or entity with any financial interest or non-financial interest in the subject matter or materials discussed in this manuscript.

Disclaimer

This paper is disseminated in the interest of information exchange. The views, opinions, findings, and conclusions reflected in this paper are the responsibility of the authors only and do not represent the official policy or position of the USDOT/OST-R, or any other State, or The University of North Carolina at Charlotte or other entity. They are based on data gathered from various online sources. This paper does not constitute a standard, specification, or regulation.

Acknowledgement

This paper is prepared based on information collected for a research project funded by the United States Department of Transportation - Office of the Assistant Secretary for Research and Technology (USDOT/OST-R) University Transportation Centers Program (Grant # 69A3551747127). The authors thank Ninad Gore, Ph.D. for his suggestions and effort on the overall project.

References

[1] Hess, D.B., 2009. Access to public transit and its influence on ridership for older adults in two US cities. Journal of Transport and Land Use. 2(1), 3–27.

[2] Zuo, T., Wei, H., Chen, N., 2020. Promote transit via hardening first-and-last-mile accessibil-

ity: Learned from modeling commuters' transit use. Transportation Research Part D: Transport and Environment. 86, 102446.
DOI: https://doi.org/10.1016/j.trd.2020.102446

[3] Five Challenges in Designing a Fully Autonomous System for Driverless Cars [Internet]. IIOT World. [cited 2022 Jul 3]. Available from: https://www.iiot-world.com/artificial-intelligence-ml/artificial-intelligence/five-challenges-in-designing-a-fully-autonomous-system-for-driverless-cars/

[4] Campus Automated Shuttle Service Deployment Initiative [Internet]. University of South Florida. Center for Urban Transportation Research. Available from: https://scholarcommons.usf.edu/cutr_nctr/46

[5] EZ10 Passenger Shuttle [Internet]. Easymile. [cited 2022 May 23]. Available from: https://easymile.com/vehicle-solutions/ez10-passenger-shuttle

[6] Autonom® Shuttle Evo [Internet]. Navya. [cited 2023 May 15]. Available from: https://navya.tech/wp-content/uploads/documents/Brochure-Autonom-Shuttle-Evo-EN.pdf

[7] Meet 3D Printed Self-driving Olli Bus [Internet]. Global Motor Media. [cited 2022 May 31]. Available from: https://www.globalmotormedia.com/self-driving-olli-minibus/

[8] Local Motors, the Startup behind the Olli Autonomous Shuttle, Has Shut Down [Internet]. [cited 2023 Jul 22]. Available from: https://techcrunch.com/2022/01/13/local-motors-the-startup-that-created-the-olli-autonomous-shuttle-has-shutdown/?guccounter=1&guce_referrer=aHR0cHM6Ly93d3cuZ29vZ2xlLmNvbS8&guce_referrer_sig=AQAAAJulmBUgNYq7e5Iv43qh7bJEqew_6_m0iJHkRGMASN7qHpU0XK6N_05L_Q7TVvOXuDPKFeh2RkoqswKiQbdJa_5HNvw3qx9lfbYEiuPMmU0KnTIjY3EziGiukFPvtInPreVLbJnHtyoTbJarVjrpCQQXfkYzU1p1FcHTuL3Q_OoM

[9] Collision with Paralympic Athlete Forces Toyota to Halt Self-driving Bus Service in Olympic Village [Internet]. [cited 2022 Aug 22]. Forbes. Available from: https://www.forbes.com/sites/peterlyon/2021/08/28/collision-with-paralympic-athlete-forces-toyota-to-halt-self-driving-bus-service-in-olympic-village/?sh=3418d197f873

[10] Haque, A.M., Brakewood, C., 2020. A synthesis and comparison of American automated shuttle pilot projects. Case Studies on Transport Policy. 8(3), 928–937.
DOI: https://doi.org/10.1016/j.cstp.2020.05.005

[11] Hsueh, G., Czerwinski, D., Poliziani, C., et al., 2021. Using BEAM software to simulate the introduction of on-demand, automated, and electric shuttles for last mile connectivity in Santa Clara County. Mineta Transportation Institute Publications.
DOI: https://doi.org/10.31979/mti.2021.1822

[12] Autonomous Shuttle Implementation and Best Practice [Internet]. Mineta Transportation Institute Publications. Available from: https://transweb.sjsu.edu/research/2321-Autonomous-Shuttle-Best-Practice-People-Mover

[13] Game Above College of Engineering and Technology Kicks off School Year by Unveiling Autonomous Shuttles and Signing Lease Agreement with American Center for Mobility [Internet]. [cited 2022 May 7]. Available from: https://today.emich.edu/story/story/11845

[14] MnDOT Autonomous Bus Pilot Project: Testing and Demonstration Summary [Internet]. MnDOT. [cited 2022 May 8]. Available from: https://rosap.ntl.bts.gov/view/dot/62752/dot_62752_DS1.pdf

[15] Australia's First Autonomous Bus Hits the Road in Perth [Internet]. Drive. Available from: https://www.drive.com.au/news/australias-first-autonomous-bus-hits-the-road-in-perth/

[16] GCP—SMART Autonomous Shuttle Trials Spring/Summer [Internet]. [cited 2022 May 5]. Available from: https://www.youtube.com/watch?v=dwL2VVXshaw

[17] Phase 3: Northcoast Regional Botanic Garden

[Internet]. BusBot. [cited 2023 Feb 2]. Available from: https://www.busbot.com.au/three-phase-trial/

[18] Rehrl, K., Zankl, C., 2018. Digibus©: Results from the first self-driving shuttle trial on a public road in Austria. European Transport Research Review. 10(2), 1–11.
DOI: https://doi.org/10.1186/s12544-018-0326-4

[19] Utah Autonomous Shuttle Pilot [Internet]. UDOT. [cited 2022 Dec 2]. Available from: http://www.avshuttleutah.com/pdfs/UtahAutomatedShuttle_FinalReport_1-3-2022.pdf

[20] Driverless Buses in Vienna's Seestadt on the Road Again [Internet]. [cited 2022 Mar 5]. Available from: https://metropole.at/driverless-buses-in-viennas-seestadt/

[21] Holo [Internet]. Autonomous mobility implementation partner. [cited 2022 Aug 11]. Available from: https://www.letsholo.com/

[22] Candiac Autonomous Shuttle [Internet]. Shared Personalized Automated Connected vEhicles (SPACE). [cited 2022 May 7]. Available from: https://space.uitp.org/initiatives/candiac-av-canada

[23] Calgary's Autonomous Shuttle Pilot Test [Internet]. Available from: https://www.tac-atc.ca/en/events-and-learning/webinars/calgarys-autonomous-shuttle-pilot-test

[24] Geneva Demonstrator Sites [Internet]. Autonomous vehicles to evolve to a new urban experience (AVENUE). [cited 2022 Aug 30]. Available from: https://h2020-avenue.eu/?portfolio=geneva

[25] Spring Training Fans in Peoria Can Get around on a Driverless Shuttle [Internet]. [cited 2022 Feb 28]. azcentral. Available from: https://www.azcentral.com/story/news/local/peoria/2020/02/05/metro-phoenix-city-offer-driverless-shuttle-rides-end-month/4666486002

[26] Two French Companies Have Launched What They Say is the World's First Driverless Public Transport Bus Service in a Suburb of Lyon [Internet]. Transport Network. [cited 2022 Apr 21]. Available from: https://www.transport-network.co.uk/100-French-driverless-bus-service-launches/13248

[27] Yellowstone Introduces Autonomous Shuttles [Internet]. [cited 2022 May 6]. Available from: https://www.foxnews.com/us/yellowstone-introduces-autonomous-shuttles

[28] Autonomous Shuttles Help Transport COVID-19 Tests at Mayo Clinic in Florida [Internet]. Mayo Clinic. [cited 2023 May 23]. Available from: https://newsnetwork.mayoclinic.org/discussion/autonomous-shuttles-help-transport-covid-19-tests-at-mayo-clinic-in-jacksonville/

[29] Electric Self-driving Shuttle back in Candiac for Summer 2019 [Internet]. [cited 2022 Jun 1]. Cision Canada. Available from: https://www.newswire.ca/news-releases/electric-self-driving-shuttle-back-in-candiac-for-summer-2019-810155449

[30] France, a Window to the Future of Europe Mobility [Internet]. Transdev. Available from: https://www.transdev.com/en/press-release/france-window-future-european-mobility/

[31] An Estonian Consortium Tests an Autonomous Bus in Greece [Internet]. Estonian World. [cited 2022 Aug 18]. Available from: https://estonianworld.com/technology/an-estonian-consortium-tests-an-autonomous-bus-in-greece