Microtransit Pilot Project in Greensboro, NC

NCDOT Project RP2023-35
Technical Report #: FHWA/NC/2023-35
January 2025

North Carolina Agricultural and Technical State University

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RESEARCH & DEVELOPMENT

Technical Report Documentation Page

1. Report No. FHWA/NC/2023-35	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle *Microtransit Pilot Project in Greensboro, NC*		5. Report Date: Jan 31, 2025 6. Performing Organization Code
7. Author(s): Ali Karimoddini, Jose Matute, Daniel Tobias, Tesfamichael Agidie Getahun		8. Performing Organization Report No.
9. Performing Organization Name and Address: North Carolina A&T State University, Autonomous Cooperative Control of Emergent Systems of Systems (ACCESS) Laboratory, Electrical and Computer Engineering Department, 1601 East Market Street, Greensboro, NC, 27411		10. Work Unit No. (TRAIS) 11. Contract or Grant No.
12. Sponsoring Agency Name and Address North Carolina Department of Transportation Research and Development Unit 1020 Birch Ridge Drive, Building B; 1549 Mail Service Center Raleigh, NC 27699-1549		13. Type of Report and Period Covered Final Report; April 15, 2023 – December 31, 2024 14. Sponsoring Agency Code: RP2023-35
Supplementary Notes:		

16. Abstract

This project investigates the feasibility of automated shuttles for deployment in urban and suburban transportation, by piloting Automated Driving System (ADS)-equipped Polaris GEM E6 vehicles in a microtransit service on a route that connects NC A&T's campus to downtown Greensboro. The project delved into the shuttles' design, particularly their sensor suite, which is crucial for navigating complex suburban landscapes. The research team performed extensive testing in a controlled environment that mimicked real-world driving conditions expected during public road demonstrations with passenger service. These tests assessed key functionalities such as mapping, localization, object recognition, and motion planning and tracking. The research team then explored the deployment of the shuttles on public streets through a one-month pilot project, analyzing the results using both objective and subjective methods, and highlighting the challenges and opportunities encountered. By comparing outcomes from both controlled and real-world settings, this project evaluated the feasibility of integrating automated shuttles into public transportation systems, thereby contributing to the ongoing discussion about the practicality and limitations of automated vehicles in urban and suburban areas. This research assists NCDOT in assessing automated shuttles as an emerging technology and supports innovation programs, particularly under the Integrated Mobility Division of NCDOT and initiatives such as the Connected Autonomous Shuttle Supporting Innovation (CASSI). Findings from this research suggest that while automated shuttles can navigate controlled environments effectively, challenges remain in real-world deployment, particularly in handling unpredictable traffic conditions and ensuring seamless interactions with other road users. Given these insights, NCDOT should consider continuing to support research and refinement of automated shuttle technology before transitioning to full-scale deployment in regular revenue service. Further pilot programs focusing on sensor fusion improvements, Vehicle to Infrastructure (V2I) communication, and enhanced route planning could help address these challenges and support the future expansion of automated microtransit solutions.

17.	18. Distribution Statement		
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 47	22. Price

Form DOT F 1700.7 (8-72) **Reproduction of completed page authorize**

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Acknowledgements

This research project was sponsored by the North Carolina Department of Transportation (NCDOT) and their continued support is greatly appreciated. The research team would like to express their appreciation to the following:

- The chair of the Steering and Implementation Committee, Sarah Searcy, for continuous engagement, support, and guidance throughout the project.
- The NCDOT team including Sarah Searcy and Amanda Goodwho helped us significantly with thee development and implementation of the incident management plan for deployment of Aggie Auto Shuttles in pubic roads.
- The NCDOT personnel serving on the Steering and Implementation Committee for this research study including Robert Sawyer, Joe Hummer, Chris Spencer, and Amanda Good during the course of this project is greatly appreciated.
- NCDOT Research and Development personnel, particularly the project manager, John Kirby.
- The project stakeholders, including NCDOT, Greensboro DOT, the City of Greensboro, Greensboro Police, Downtown Greensboro Inc., industrial partners, local community members and businesses, and various units across NC A&T University, trusted and invested in our research team and assisted with the planning and implementation of this project.
- Kevin Lacy, former Chair of the Steering and Implementation Committee.

EXECUTIVE SUMMARY

North Carolina has distinctive transportation challenges and needs. Conventional fixed-route transit may not effectively meet sporadic transportation demands over laorge geographic areas with low population densities. Microtransit service can address this challenge in low-demand rural areas by providing more efficient and customer-focused transportation services via flexible routing and scheduling while reducing the transportation cost due to smaller sizes of vehicles and the adoption of ridesharing strategies. Several communities in North Carolina have started microtransit pilot programs such as the GoWake SmartRide NE, Wilson RIDE, and RideMICRO in the Wilmington area. In parallel, the North Carolina Department of Transportation (NCDOT) has piloted automated vehicles in transit applications through the Connected Autonomous Shuttle Supporting Innovation (CASSI) program. Along with these efforts, NCDOT has sponsored the research project, "Developing and Operationalizing a Testbed of Connected Self-driving Shuttles to Test and Develop CAV applications in North Carolina" (NCDOT RP 2022-16). The developed Connected Autonomous Vehicle (CAV) testbed consists of three Polaris GEM E6 low-speed vehicles that are outfitted with automated vehicle technology and are being tested individually on a test track at NC A&T State University (NC A&T)'s Gateway Research Park. Leveraging the efforts under NCDOT RP 2022-16, this project investigates the feasibility of automated shuttles for deployment in urban and suburban transportation, by piloting the Automated Driving System (ADS)-equipped Polaris GEM E6 vehicles in a microtransit service on a route that connects NC A&T's campus to downtown Greensboro. The project delved into the shuttles' design, particularly their sensor suite, which is crucial for navigating complex suburban landscapes. The research team performed extensive testing in a controlled environment that mimicked real-world driving conditions expected during public road demonstrations with passenger service. These tests assessed key functionalities such as mapping, localization, object recognition, and motion planning and tracking. The research team then explored the deployment of the shuttles on public streets through a one-month pilot project, analyzing the results using both objective and subjective methods, and highlighting the challenges and opportunities encountered. By comparing outcomes from both controlled and real-world settings, this project evaluated the feasibility of integrating automated shuttles into public transportation systems, thereby contributing to the ongoing discussion about the practicality and limitations of automated vehicles in urban and suburban areas.

The field test evaluation demonstrated that the Aggie Autonomous Shuttles performed well in predefined, structured routes, successfully following the desired paths and responding to basic traffic scenarios. However, challenges arose in handling complex urban environments, particularly

when dealing with signalized and non signalized intersections or lane sharing scenarios. Beyond its technical contributions, this project played a crucial role in increasing public awareness and trust in automated vehicle technology. By allowing community members to experience automated shuttles firsthand, it fostered a greater understanding of the technology's capabilities, limitations, and safety measures. Public engagement through this pilot project, surveys, and outreach initiatives helped build confidence in the viability of automated microtransit solutions as an effective transportation option.

This research assists NCDOT in assessing automated shuttles as an emerging technology and supports innovation programs, particularly under the Integrated Mobility Division of NCDOT and initiatives such as the Connected Autonomous Shuttle Supporting Innovation (CASSI). Findings from this research suggest that while automated shuttles can navigate controlled environments effectively, challenges remain in real-world deployment, particularly in handling unpredictable traffic conditions and ensuring seamless interactions with other road users. Given these insights, NCDOT should consider continuing to support research and refinement of automated shuttle technology before transitioning to full-scale deployment in regular revenue service. Further pilot programs focusing on sensor fusion improvements, Vehicle to Infrastructure (V2I) communication, and enhanced route planning could help address these challenges and support the future expansion of automated microtransit solutions.

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1 Introduction

This project investigated the feasibility of automated shuttles for deployment in urban and suburban transportation, focusing on the Aggie Auto Shuttles pilot project conducted by researchers at North Carolina A&T State University in Greensboro, North Carolina, USA. It delved into the shuttles' design, particularly their sensor suite, which is crucial for navigating complex suburban landscapes. The research team performed extensive testing in a controlled environment that mimicked real-world driving conditions expected during public road demonstrations with passenger service. These tests assessed key functionalities such as mapping, localization, object recognition, and motion planning and tracking. The research then explored the deployment of the shuttles on public streets, analyzing the results using both objective and subjective methods, and highlighting the challenges and opportunities encountered. By comparing outcomes from both controlled and real-world settings, the project evaluated the feasibility of integrating automated shuttles into public transportation systems, thereby contributing to the ongoing discussion about the practicality and limitations of automated vehicles in urban and suburban areas.

2 Research Objectives

The goal of this project was to pilot Automated Driving System (ADS)-equipped, low-speed vehicles in a microtransit service to connect NC A&T State University and downtown Greensboro.

This was achieved through the following objectives:

- **Objective 1:** Identifying the appropriate route and safe stops in coordination with stakeholders,
- **Objective 2:** Developing the in-vehicle data collection systems and surveys to assess public perception and acceptance of the AVs,
- **Objective 3:** Building a map and addressing the technical challenges for deployment of vehicles on the identified route,
- **Objective 4:** Actual deployment of the autonomated vehicles between the NC A&T campus and downtown Greensboro, and
- **Objective 5:** Analyzing and reporting the collected data and the deployment process.

The funding for this project supported a range of critical activities necessary for the successful evaluation and deployment of automated shuttles. It covered the acquisition and modification of

Polaris GEM E6 low-speed vehicles with advanced automated driving system (ADS) technology, including LiDAR, cameras, radar, and computing hardware. Additionally, the funds facilitated software development for localization, mapping, and route planning, as well as testing in both controlled environments and real-world conditions.

The project also supported pilot program operations, including vehicle maintenance, data collection, and performance evaluation. Beyond technical development, funding was allocated for public outreach efforts such as stakeholder engagement, passenger surveys, and educational events to increase awareness and trust in autonomous vehicle technology.

The piloted project helped NCDOT assess this emerging technology of automated shuttles by evaluating their operational efficiency, safety performance, and integration within existing transportation systems. This included examining real-world deployment challenges, regulatory considerations, and public perception to determine the feasibility of broader adoption. Additionally, funding supported workforce development efforts, equipping faculty, graduate students, and engineers with expertise in system integration, safety assessments, and data analysis. This investment enables the research team to refine, customize, and deploy this testbed of automated shuttles for future pilot projects, further advancing the adoption of autonomous vehicle technology in public transportation.

3 Literature Review and Gap Analysis

Low-Speed Automated Vehicles (LSAVs) [1] represent a novel form of public transportation that aims to enhance mobility and accessibility, particularly for the first and last mile of a journey. Unlike traditional shuttle buses, these vehicles operate without a human driver and with a high level of automation enabled by Automated Driving System (ADS) capabilities, relying on advanced sensors and software to navigate (predefined) routes. Also, these vehicles are smaller and have lower passenger capacity, which allows for more flexible and responsive service in suburban and rural areas characterized by a dispersed and low ridership. However, the feasibility and impact of LSAVs require thorough evaluation through pilot projects, which can provide valuable insights into their real-world performance, safety, efficiency, and economic viability under varied traffic and operating conditions [2].

Demonstrations conducted in controlled environments have yielded significant insights into the operational efficiency of LSAVs within transportation frameworks. This allows the identification of driving scenarios with a high level of abstraction in the concept phase that can be concretized throughout the development process [3]. This approach safely addresses representative driving scenarios to prepare for mixed-traffic environments that include pedestrians, cyclists, and other road occupants [4]. Real-world pilot programs have been meticulously executed in semi-controlled, yet realistic settings to handle these situations, but often with low speeds and limited passenger capacities [5]. Some studies have proposed methodologies for first-and-last-mile operations with LSAVs, including context understanding, key factors definition, stakeholder surveying, and operational scenario formulation [6]. The choice of predefined routes allows for deploying advanced navigation systems, enabling the simulation of passenger pick-up and drop-off scenarios [7]. Likewise, researchers have explored utilizing cloud brain approaches to tackle challenges associated with large-scale LSAV implementations [8]. However, the complexity of real-world scenarios makes it challenging to design computer systems that can anticipate and handle all possible situations [9]. Hence, it is crucial to recognize that investigations conducted in semi-controlled driving environments can serve only as valuable initial assessments [10].

Validating the operational capability of LSAVs under authentic traffic conditions is crucial for their continued progress and successful integration into broader transportation systems. LSAVs have been typically deployed in dense urban areas, like university campuses, stadiums, office parks, transit stations, entertainment areas, and downtown areas [11]. Some demonstrations have highlighted the need for precise mapping or alternative localization mechanisms to mitigate potential disruptions from satellite signal loss [12]. Outcomes from some demonstrations further support for integrating sensor data to foster a holistic understanding of the surrounding environment [13], enhancing compliance with traffic regulations, particularly concerning yielding to vulnerable road users [14], and mitigating instances of overly cautious driving that could impede traffic flow and lead to confusion among fellow road occupants [15].

In this study, through the Aggie Auto Shuttles pilot project, the research team investigated the deployment of automated shuttles in urban and suburban environments. This study details the technical aspects of the Aggie Auto Shuttles, including their sensor suite, hardware architecture, and software stack, and describes the testing procedures and results obtained from operation in a controlled environment before deployment on public streets. This study also documents the preparations for public road demonstration with passenger service under mixed-traffic scenarios. This study also discusses the results obtained from the pilot in downtown Greensboro, where the shuttles operated from September 18 through Oct 13, 2023 on a 1.49 mile (2.4 km) route conneecting the neighborhood of N.C. A&T campus to the Greensboro's Children's Museum. In summary, the contributions of this project include:

- Development of a fleet of automated shuttles capable of operating in urban and suburban environments, with a focus on serving underserved communities,

- Successful test and deployment of the Aggie Auto Shuttles in a real-world public road demonstration, gaining valuable insights into the challenges and opportunities of automated shuttle services,
- Evaluation of the ADS of the shuttles and root-cause analysis of instances of disengagement of driving automation of the vehicles
- Collaboration with local and state transportation agencies, demonstrating the importance of interagency cooperation and public involvement in the development and deployment of automated vehicle technologies.

Figure 1. Sensor suite consisting of: 1) Velodyne VLP-32C, 2) 3x Velodyne VLP-16, 3) Dual Antenna + Novatel PwrPak7D-E2, 4) 2x Lucid Triton Camera IMX265, 5) RaDAR Delphi ESR, and 6) MAKO 5G Dome Antenna + Cradlepoint R1900.

4 The Aggie Auto Shuttles

The Aggie Auto Shuttles are automated vehicles designed for developing, testing, and demonstrating different ADS functionalities, aiming to ultimately enhance transportation options in rural areas and facilitate connectivity in regions lacking robust public transit infrastructure. The Aggie Auto Shuttles use a Polaris GEM e6, a six-passenger electric vehicle capable of achieving a top speed of 25 mph (40 km/h), as the base vehicle and integrate state-of-the-art hardware and software technologies. A sensor suite was designed and integrated to address semi-urban driving scenarios as depicted in Fig. 1.

The VLP-32C LiDAR was positioned in an elevated manner using aluminum frames at the top center of the vehicle to facilitate environmental perception within medium and long ranges. Conversely, three VLP-16 LiDARs were situated in the roof rack above the windshield on the right, left, and center, aiming to mitigate blind spots within shorter-range areas. Furthermore, a Novatel PwrPak7D-E2, equipped with an Inertial Navigation System (INS), served as a localization source, capable of receiving signals from the Global Navigation Satellite System (GNSS), along with Real Time Kinematic (RTK) corrections provided by public ground stations. Two antennas were integrated into the GNSS+INS receiver and installed on the rear section of the roof rack at each side to enhance orientation accuracy. To increase the perception redundancy, two Lucid Triton IMX265 cameras were installed on the frontal side of the roof rack, each one with different focal lenses of 0.47 in (12 mm) and 0.63 in (16 mm), to capture wider and narrower fields of view, respectively. Also, one Delphi ESR RaDAR with a mid-long measurement range was installed in the frontal bumper. Finally, a Cradlepoint R1900 router with an MAKO Dome Antenna was integrated to enable 5G connectivity and Wi-Fi.

4.1 Developing a User-Friendly App for Vehicle Tracking

The shuttles were able to connect to the riders via a cloud-based application software. This was made feasible by connecting the shuttles to the cloud through 5G internet communications, sharing their real-time location. Initially, the research team planned to include features such as booking a ride, barcode scanning at pickup time, and sharing seat occupancy data. However, due to highly unpredictable travel demands, the research team decided to disable these features and consider them for future pilot programs. The application software, therefore, was limited to tracking the location of the vehicles so that the riders could estimate the arrival time. Fig. 2 shows a snapshot of the live tracking of the vehicles during the pilot project.

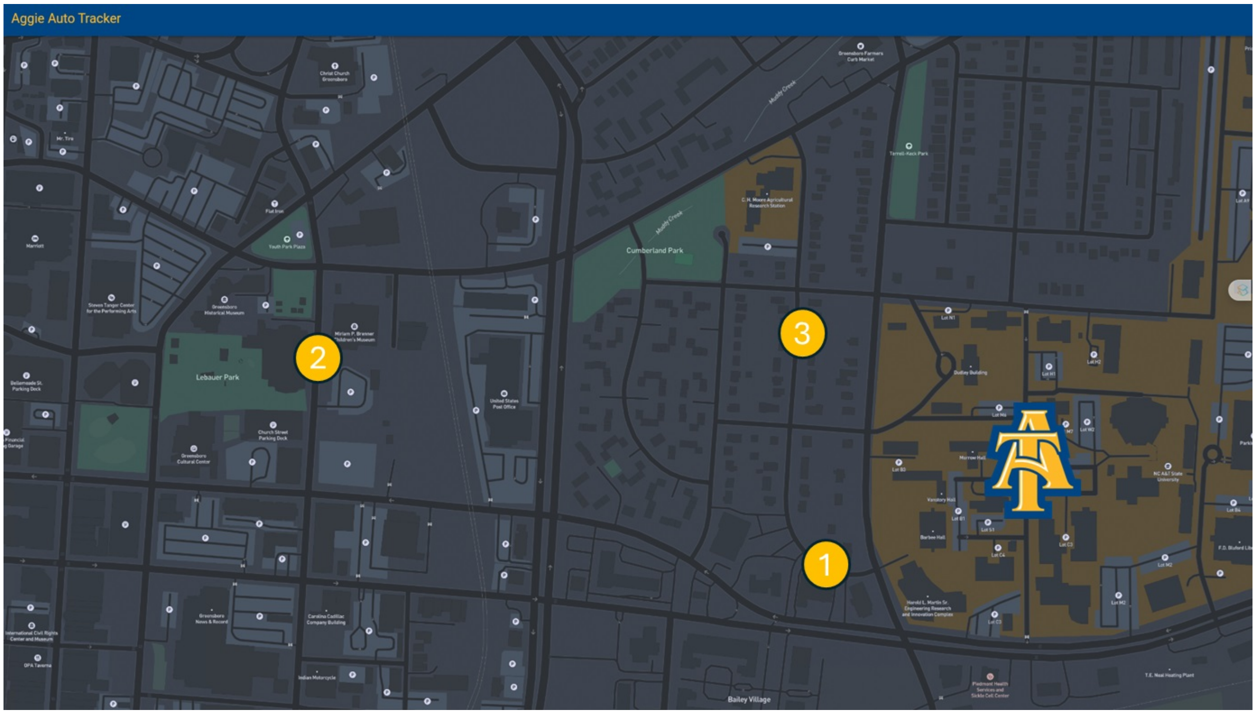


Figure 2. A snapshot of the application software for live tracking of the Aggie Auto Shuttles, where the orange circle and the associated numbers were showing the live location of shuttles.

5 Closed Course Test of Aggie Auto Shuttles

The developed Aggie Auto Shuttles consisted of three Polaris GEM E6 low-speed vehicles that were outfitted with automated vehicle technology and were tested individually. The performance assessment was conducted in a realistic driving environment, testing several driving scenarios under controlled conditions. In this section, the testing setup related to the closed course test track and the verification of systems before the public road demonstration are described.

5.1 Testing Setup

The Gateway Research Park - North Campus (Greensboro, NC), hosts a 1.36 mile (2.2 km) long test track, a controlled driving environment for research and development of ADS technologies. This test track, shown in Fig. 3, provides a versatile setting for testing and validation tasks before automated vehicles are deployed on public roads, offering a diverse range of challenging driving scenarios, including roundabouts, intersections, crossings, traffic signs, and road markings, which replicate suburban driving conditions.

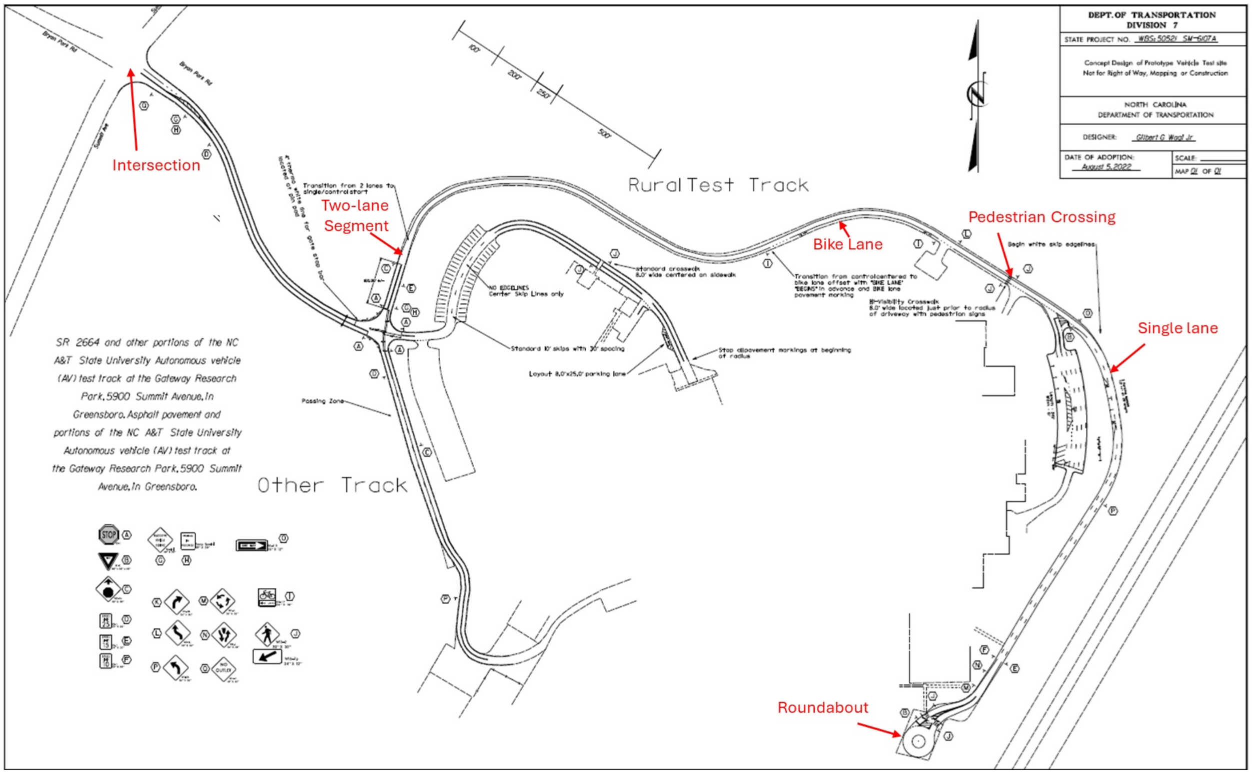


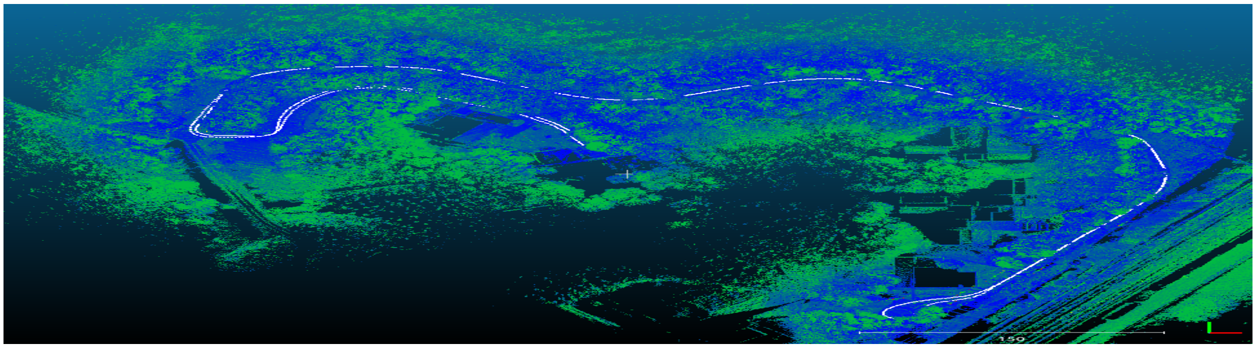
Figure 3. The closed course test track at NC A&T Gateway Research Park for testing LSAVs under different driving scenarios, including roundabouts, intersections, crossings, and traffic signs.

5.2 Systems Verification

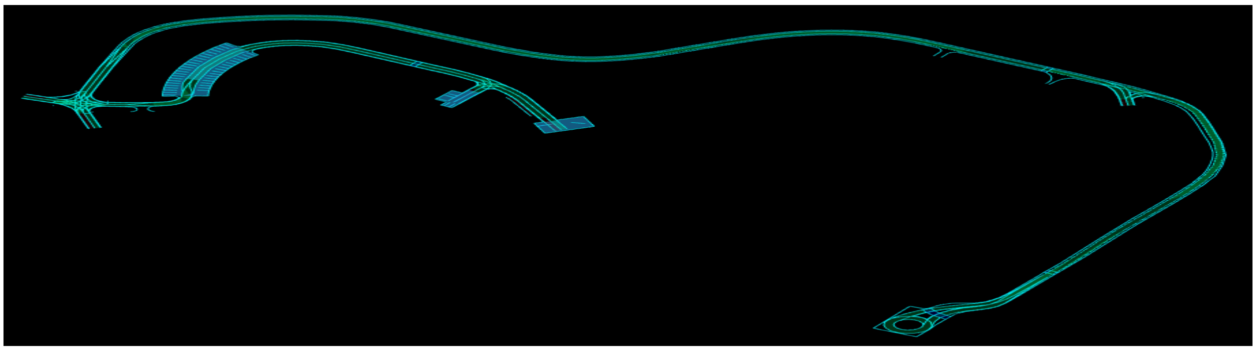
A rigorous verification procedure was conducted at the NC A&T test track to evaluate each system. This process allowed the research team to identify potential issues considering the driving scenarios expected in the public road demonstration, guaranteeing the safe and reliable operation of the Aggie Auto Shuttles. The verification process involved the following key components:

5.2.1 Mapping Process

Fig. 4.a depicts the mapping process consisting of a detailed high-definition 3D point cloud representation of the test track. The procedure involved a single pass along the route (i.e., the white dots represent the driven trajectory) to build a complete point cloud of the surrounding environment, including static elements such as buildings, trees, and road infrastructure [16]. Fig. 4.b shows the Lanelet2 map that the research team manually created to include relevant information for the ADS, like geometric details, routing information, and semantics of the driving environment [17]. These detailed maps served as the primary references for downstream systems during the testing and deployment phases.



(a)



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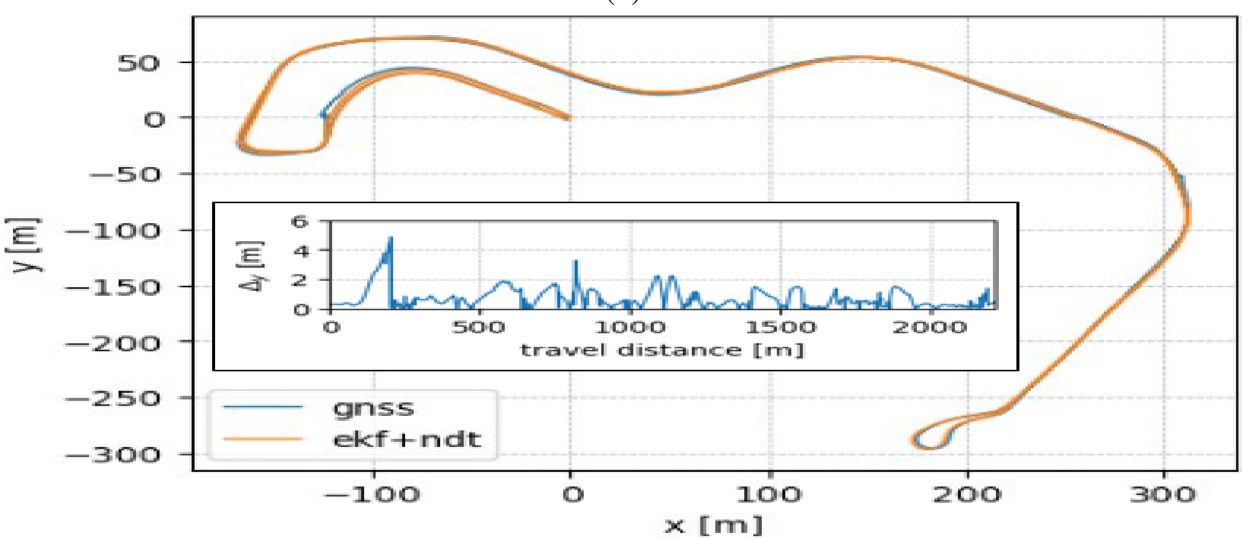


(c)

Figure 4. Visualizations of the (a) PCD and (b) Lanelet2 maps of the test track obtained from the LiDAR mapping. This Lanelet2 map contains geometric details, routing information, and semantics of the driving environment, including lane boundaries, traffic signs, crosswalks, merging lanes, intersections, and pull-over areas, as relevant driving use cases for the pilot project. (c) A comparison of GNSS and EKF+NDT localization approaches along the test track. The lack of GNSS accuracy is due to multipath error caused by the forested environment.

5.2.2 Localization Process

Fig. 4.c illustrates the LiDAR localization system that relies on an EKF combined with NDT as its core approach. The EKF+NDT approach is the foundation of the 'ndt_scan_matcher' algorithm [18, 19]. The performance of this EKF+NDT localization is compared to that of the available GNSS-based approach. As shown, the GNSS accuracy is compromised by environmental factors, such as multipath errors caused by the forested areas, resulting in a cross-track trajectory difference (Δ_y) of over 13.1 ft (4 m) compared to the LiDAR-based localization. Consequently, the LiDAR-based localization proved to be the most robust alternative, and hence, it was selected as the primary localization source in this research [20].

5.2.3 Object Recognition

Fig. 5 depicts the process of object recognition using pure LiDAR data. The RGB image on the left shows a color image of the current environment ahead of the vehicle, while the LiDAR point cloud representation is displayed on the right. The LiDAR data is segmented into clusters, represented by the bright white dots, which group points that likely belong to the same object, allowing the system to classify these detected object proposals into categories such as buses, cars, pedestrians, or bicycles [21,22]. In the example shown, three different cars ahead of the vehicle are recognized, and relevant information like ID, type, and velocity is displayed.

Due to the early development stage, object recognition from cameras and RaDAR is not employed, and the system relies solely on processing and visualizing the pure LiDAR data as the primary means of identifying surrounding objects on the test track and during the public road demonstration, allowing the research team to first optimize the core perception capabilities of the Aggie Auto Shuttles before potentially incorporating additional sensor modalities in the future.

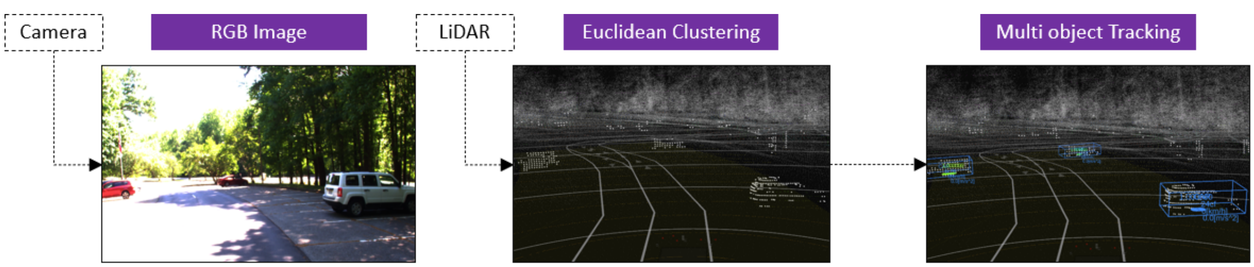


Figure 5. The process for 3D object recognition: LiDAR data is used to cluster points into smaller parts to classify objects. Subsequently, the detections are processed over a time series, assigning each object an identification number and estimating its velocity.

5.2.4 Planning and Control

Fig. 6 shows the planning and control performance while navigating through a set of test cases, which represent driving scenarios available in the controlled test environment [23,24] and expected to be encountered during the public road demonstration, including pull-over, adaptive cruise control, curve deceleration, crosswalk, intersection, and stop line management.

Pull-Over: Fig. 6.a depicts the pull-over maneuver execution. As the vehicle approaches the pull-over location, the path is dynamically replanned to execute a smooth and safe maneuver, allowing the vehicle to park at the road shoulder.

Adaptive Cruise Control: Fig. 6.b demonstrates the adaptive cruise control functionality. A safe following distance from the lead vehicle is maintained, adjusting its speed accordingly to ensure a comfortable and efficient driving experience. The range of speed from 0-25 mph (40 km/h) is evaluated considering static and dynamic objects ahead on the road.

Curve Deceleration: Fig. 6.c shows the curve deceleration test case. As the vehicle approaches a sharp curve, the planning and control module reduces the speed to ensure a safe and stable turning maneuver.

Crosswalks: Fig. 6.d illustrates the behavior when approaching a crosswalk. The behavior planning system considers the presence of pedestrians in the vicinity of a crosswalk and adjusts the speed and trajectory to yield the right-of-way and ensure the safety of vulnerable road users.

Intersections: Fig. 6.e depicts the handling of intersections. The behavior planning module considers the prediction of moving objects participating in the intersection (e.g., a vehicle moving and crossing the intersection), and planning the velocity for turning right or left at the intersection to avoid risk with other oncoming objects.

Stop Line: Fig. 6.f shows the behavior when approaching a stop line. The system considers the existence of stop lines, and the planning and tracking modules bring the vehicle to a complete stop at a 1 m distance.

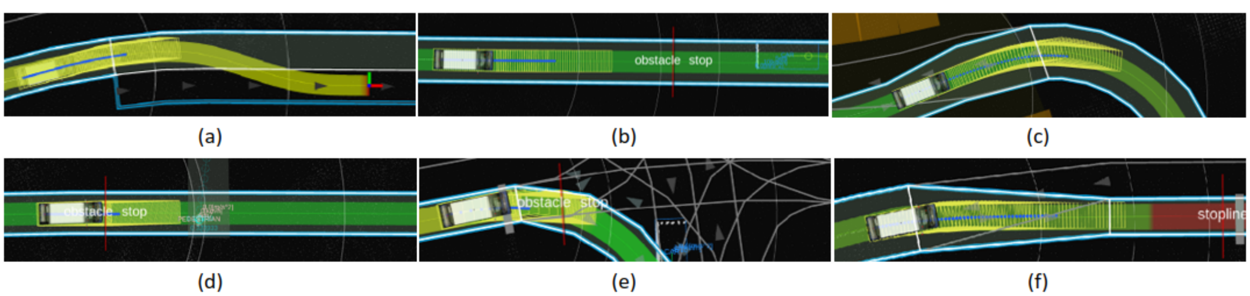


Figure 6. Use case driving scenarios considered for testing in the controlled environment and expected in public road demonstration: a) pull-over, b) adaptive cruise control, c) curve deceleration, d) crosswalk, e) intersections, and f) stop lines.

6 The Pilot Deployment of the Aggie Auto Shuttles

Conventional fixed-route transit may not effectively meet sporadic transportation demands over large geographic areas with low population densities. Microtransit services can address this challenge in low-demand urban or suburban areas by providing more efficient and customer-focused transportation services via flexible routing and scheduling while reducing costs due to smaller sizes of vehicles and the adoption of ridesharing strategies. The N.C. Department of Transportation's Integrated Mobility Division has made significant efforts to improve mobility options, including on-demand microtransit [25]. A comprehensive report on on-demand microtransit has been developed by the NCDOT Integrated Mobility Division and is available at [26].

Aggie Auto Shuttles have been developed to ultimately provide better transportation choices in rural and underserved communities that have little to no access to public transportation as well as connecting disconnected communities. After rigorous testing of the Aggie Auto Shuttles by researchers at North Carolina A&T State University (NC A&T), the team aimed to pilot the deployment of automated shuttles in Greensboro and connect the underserved communities around NC A&T to establishments in downtown Greensboro. The website developed for the pilot project is available at https://www.aggieauto.com/.

6.1 The Pilot Program Objectives

The ADS-equipped Polaris GEM E6 were piloted to provide microtransit service on a route that connects the neighboring area of NC A&T's campus to downtown Greensboro. This was achieved through (1) Identifying the appropriate route and safe stops in coordination with stakeholders, (2) Developing the in-vehicle data collection systems and surveys to assess the acceptability and public perception of LSAVs, (3) Developing communication systems to connect LSAVs to a control room, to the cloud, and the users, (4) Developing a user-friendly application for users to request a ride and track the vehicles, (5) Building a map and addressing the technical challenges for deployment of vehicles throughout the identified route, (6) Actual deployment of the automated vehicles between NC A&T's campus and downtown Greensboro, and (7) Analyzing and reporting data collected from the deployment process.

6.2 Legal, Policy, and Regulatory Requirements

The legal, policy, and regulatory requirements for the vehicles were thoroughly considered for deployment on public roads in North Carolina. Specifically, all vehicles comply with Federal Motor Vehicle Safety Standards (FMVSS). In collaboration with the North Carolina Division of Motor Vehicles (NCDMV), the inspection, titling, and registration of the vehicles were completed. Also, the North Carolina streets and highways G.S. 20-4.01(h) was complied with, requiring the vehicles to:

- Comply with Articles 3, 3A, 7, 11, and 13 of Chapter 20; comply with applicable federal law and regulations; and be certified by federal regulations in 49 C.F.R. Part 567 as complying with Federal Motor Vehicle Safety Standards (FMVSS) and bears the required certification label or labels. [*The vehicles conform to FMVSS and have been registered with DMV.*]
- Meet the requirements set in G.S. 20-401(g) for stopping in the event of a crash. Also, the vehicle can achieve a minimal risk condition (a term defined in S. 20-400(4)). [*The vehicles always had a backup driver behind the steering wheel. The automated driving functionalities were tested. In particular, tests were conducted by the research team under different driving scenarios to attest that the backup driver could safely take over control.*]
- Register the vehicles following Part 3 of Article 3 of Chapter 20. [*The vehicles were registered with DMV.*]
- Put in place a liability policy meeting the requirements of G.S. 20-279.21. [*The research team coordinated with an insurance company and attested that there is always a backup driver behind the steering wheel that can take over the control of the vehicle, so all parties agreed to treat the vehicles as regular human-driven vehicles, and liability insurance was acquired accordingly.*]

6.3 Stakeholder Engagement

A considerable amount of time was required for planning and preparation before the Aggie Auto Shuttles were deployed on public roads and offered passenger service, engaging with different stakeholder groups, including:

- **Public Agencies and Local Government:** North Carolina DoT, Greensboro DoT, City of Greensboro, Greensboro Police, Greensboro Fire Department
- **Industrial Partners:** Verizon, Volvo, Google, Waymo
- **Local Community:** Downtown Greensboro Inc., Local businesses
- **Different Divisions Across NCA&T University:** College of Engineering, University Relations, University Police, University Community Outreach, University Advancement, University External Affairs, University Parking Services

Through these meetings different topics were discussed including:

- Selecting the route to operate on
- Identifying the bus stops
- Assessing the challenging driving scenarios and the associated risks
- Developing and implementing an incident management plan
- Liability insurance coverage plan

As part of this stakeholder engagement effort, the research team collaborated with NCDOT to organize a workshop for first responders on Sep 13, 2023 to discuss the incident management plan for Aggie Autonomous Shuttles prior to their public deployment. The workshop was well attended by over 25 first responders from Several units from University Police Dept, the Greensboro Fire Department, and the Greensboro Police Dept.

The attendees were engaged with the researchers at NCA&T with an inspiring willingness to make the best of the workshop and filled with curiosity, questions and excitement about the opportunities and challenges that Aggie Auto project and similar efforts may bring to the community, particularly in terms of incident management.

The workshop consisted of two parts, an overview of the project and a hands-on demonstration where key points were highlighted and discussed with the focus on:

1. Sources of Hazard
2. Emergency Main Battery Cut-Off

The format of workshop was interactive, incorporating the feedback from first responders into the developed incident management plan. The discussion also included topics such as incident categorization, emergency contacts and responsibilities, incident response flow, training needs, and communications plan.

The research team also was able to collect useful feedback from first responders regarding the Incident Response Flow and ways to better identify and access the most important components of the vehicles such as electrical parts in case of an emergency.

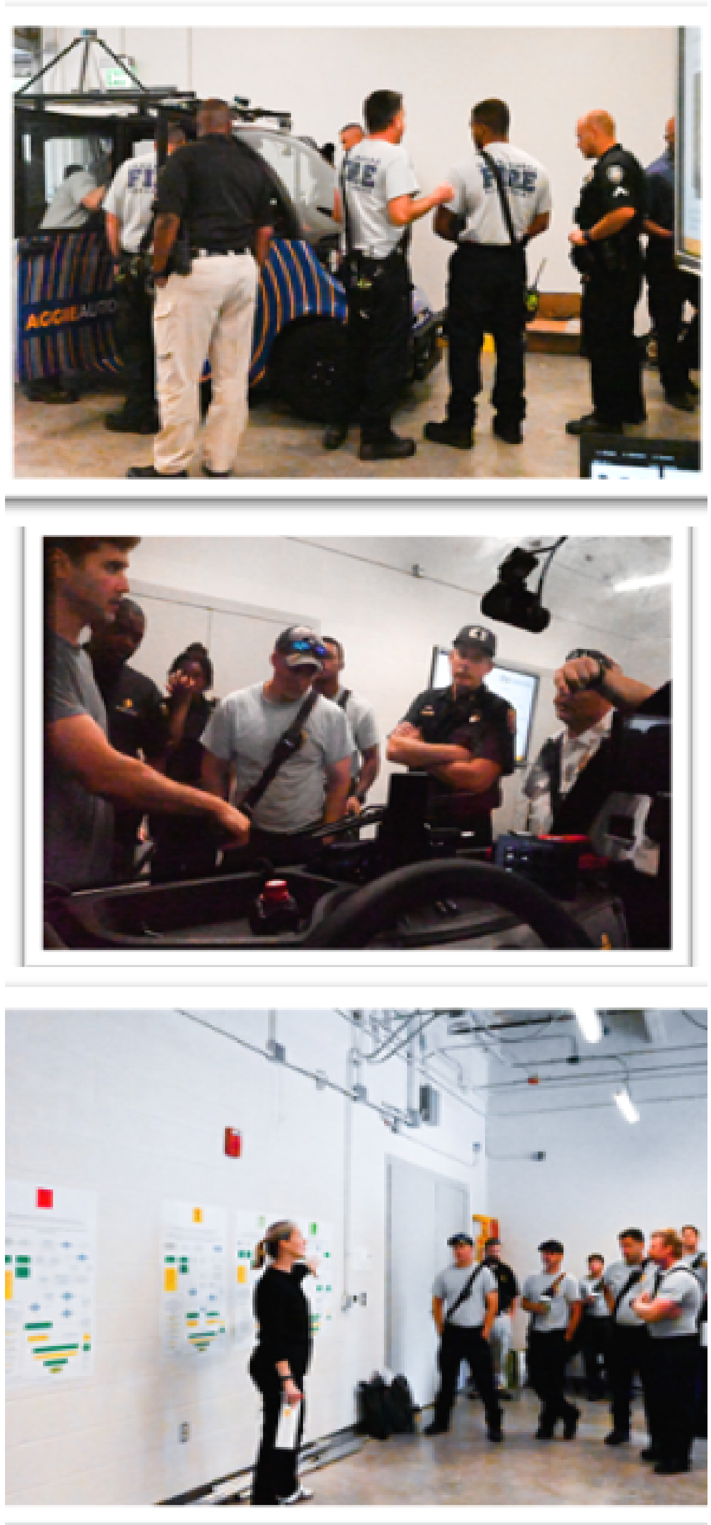


Figure 7. The research team collaborated with NCDOT to organize a workshop for first responders on Sep 13, 2023 to discuss the incident management plan for Aggie Autonomous Shuttles prior to their public deployment.

6.4 Selection of the Route of the Aggie Auto Shuttles

Considering several factors, the route was selected in collaboration with the City of Greensboro. Most of the route was either multi-lane or the speed limit was less than 25 mph (40 km/h) (the maximum speed of the Polaris GEM). The selected route ensured that the low speed of the shuttles did not significantly impact traffic. In addition, two safe stops were identified for picking up and dropping off passengers: one was in front of the Harold L. Martin Sr. Engineering Research and Innovation Complex at N.C. A&T University and the other one was in front of the Greensboro Children's Museum, giving riders access to the Greensboro Public Library, Greensboro History Museum, Greensboro Cultural Center, LeBauer Park, Governors Court, and downtown businesses and restaurants.

Fig. 8 depicts the route of the pilot project, which consists of a mix of urban and suburban roads, each presenting unique challenges under different driving scenarios. The urban roads, depicted in blue, consisted of one-way roads with multiple lanes merging and diverging. The suburban roads, shown in red, consisted of reversible roads with a single lane, which are sections that have only one lane but allow traffic to flow in both directions.

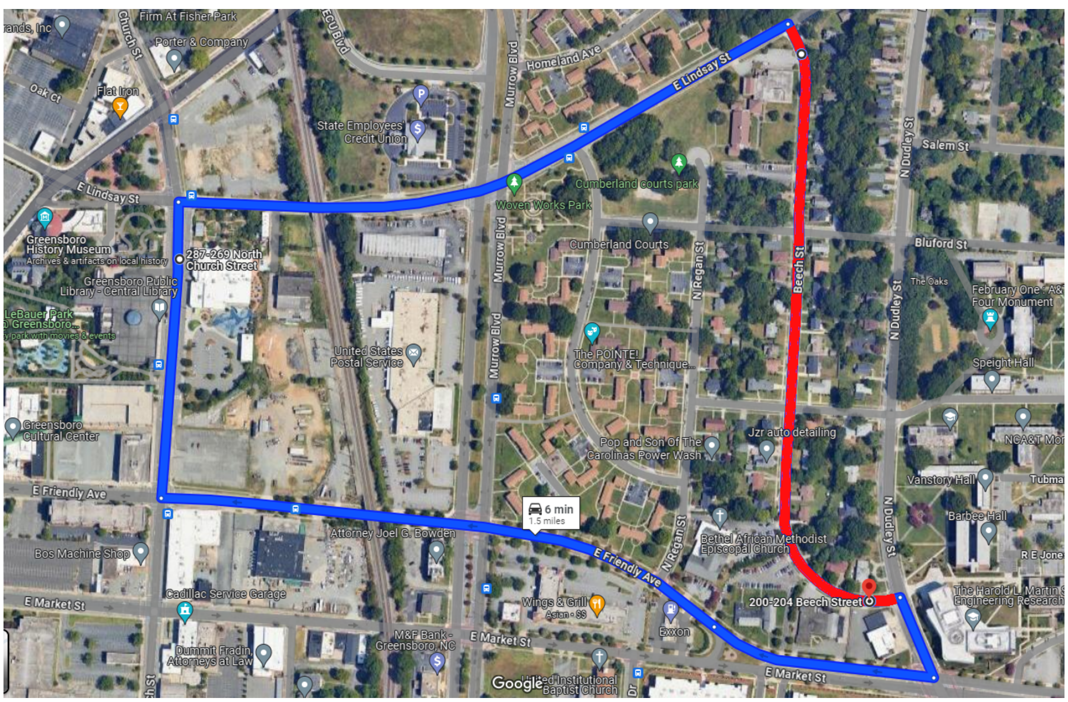
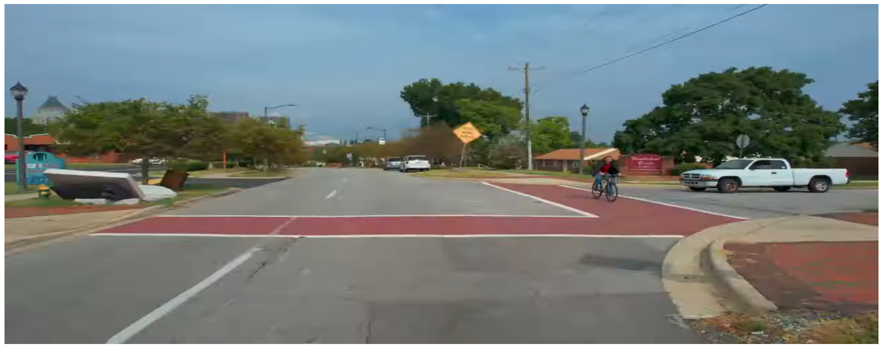


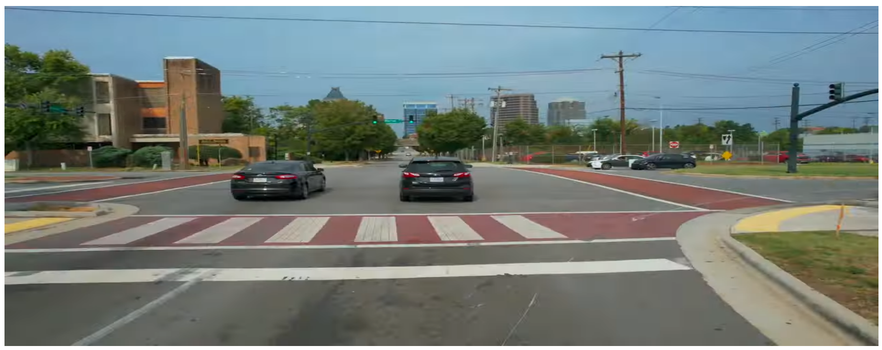
Figure 8. The selected route consisted of a round trip of 1.49 mile (2.4 km) within a mix of urban and suburban driving environments, with one-way (blue) and reversible (red) lanes, respectively. Two stops were located near the NC A&T campus (202 Beech St) and downtown Greensboro, NC (222 N Church St).

Fig. 9 shows instances of the urban part of the route requiring different driving maneuvers, such as small intersections with pedestrian crossings, big intersections with traffic lights, merging and diverging lanes, and multiple lanes with parking areas near the second shuttle stop. On the other hand, Fig. 10 presents instances of the suburban part of the route, including reversible road scenarios, narrow roads with parked cars on both sides, two-way intersections with unmarked pedestrian crossings, and curved roads with parking areas near the first shuttle stop. A classification of the Operational Design Domain (ODD) of the entire driving scenario is described in Tab. 1.

In this pilot, a traffic light recognition approach (e.g., vehicle-to-infrastructure (V2I) communication) was not available for intersections. Hence, to ensure a safe maneuver, the backup driver was responsible for performing the task of stopping the vehicle at red lights at signalized intersections.



(a) Small intersections with marked pedestrian crossings



(b) Large intersections with traffic lights and marked pedestrian crossings

(c) Straight roads with lane merging or divergence

(d) Straight roads of one or multiple lanes with parking areas near the second shuttle stop

Figure 9. Instances of the urban part of the route include (a) small intersections with marked pedestrian crossings, (b) big intersections with traffic lights and marked pedestrian crossings, (c) straight roads with lane merging or divergence, and (d) straight roads of one or multiple lanes with parking areas on the right side near the second shuttle stop.

(a) Transitions from a one-way road potentially encroaching on oncoming vehicles

(b) Narrow roads with parked cars on both sides

(c) Two-way stop intersections with unmarked pedestrian crossings

(d) Curved roads with parking areas on the right side near the first shuttle stop

Figure 10. Instances of the suburban part of the route include (a) transitions from a one-way road potentially encroaching on oncoming vehicles, (b) narrow roads with parked cars on both sides, (c) two-way stop intersections with unmarked pedestrian crossings, and (d) curved roads with parking areas on the right side near the first shuttle stop.

Table 1. ODD classification of the pilot project.

Top-level	**Second-level**	**Third-level**
Physical Infrastructure	Roadway Type	Urban and suburban Single and multiple lanes (up to 4) One-way and reversible lanes Intersections: Signalized, crosswalk, and 2-way stop
	Roadway Surface	Asphalt road Asphalt and brick crosswalks Potholes (only in reverse lanes)
	Roadway Edges	Lane markings Curb (concrete)
	Roadway Geometry	Straightaways Curves from 19.6 ft (6 m) radius Lane width from 9.8 ft to 12.1 ft (3m to 3.7m
Operational Constraints	Speed Limit	From 20 mph (32 km/h) to 35 mph (56 km/h)
	Traffic Condition	Normal from 11:00 to 13:00
Objects	Signage	Stop, yield, and pedestrian crossing Traffic lights Construction signage
	Roadway Users	Stopped and moving vehicles, pedestrians, and cyclists
	Non-roadway	Pedestrians and cyclists
Connectivity	C-V2X	5G (Verizon)
Environmental Conditions	Weather	Rain (from light to heavy)
	Illumination	Daylight with overhead sun

Figure 11. Fleet of Aggie Auto Shuttles used in the pilot project. A minimum of two shuttles were deployed to provide passenger services. Positioned at designated areas, the shuttles departed synchronously, maintaining a continuous presence to promptly serve new passengers. A third vehicle was used as a backup or when there was a higher demand.

6.5 Schedule of the Pilot Project

The Aggie Auto Shuttles provided service to the public, on weekdays between 11:00 and 13:00, covering the period from Sep. 18, 2023 through Oct. 13, 2023. The route connected the NC A&T campus to downtown Greensboro. These two areas are about 0.75 mile (1.2 km) apart, and a trip from NC A&T's campus to downtown Greensboro takes about 8 min. An image of the fleet of Aggie Auto Shuttles driving over a section of the route (E Friendly Ave) is shown in Fig. 11. A video demonstration of the Aggie Auto Shuttles is available at https://www.youtube.com/watch?v=vPznZwcn1Us.

7 Technical Assessment of the Pilot Project

The research team used objective and subjective approaches to conduct experiments and collect data to assess the public road demonstration of the Aggie Auto Shuttles. A detailed analysis of disengagements from automated driving mode is presented, considering the number and location of this kind of event along the route as well as root-cause analysis of the disengagement events.

Further, a discussion is given to capture the lessons learned during the public road demonstration from the point of view of the safety drivers, considering the challenges for automated vehicle operation on public roads, such as interaction with other road users, localization improvements, digital infrastructure, comfort and safety experience, charging, and vehicle maintenance.

7.1 Handover vs Takeover Analysis

The handover (HO) vs. takeover (TKO) analysis refers to the instances where the safety driver releases the steering wheel to give control to the ADS to perform the Dynamic Driving Task (DDT), i.e., all real-time operational and tactical functions required to operate a vehicle in traffic, or grabs the steering wheel to control the vehicle to perform the DDT, respectively. This analysis is based on data obtained from each Aggie Auto Shuttle during the period. The research team recorded relevant variables describing transition events (i.e., HO or TKO) in a CSV file, including event date, event time, x-coordinate location, y-coordinate location, current speed, driven distance, and driven time.

Fig. 12 illustrates the number and locations of HO (i.e., transitions to automated mode) and TKO (i.e., transitions to manual mode) that occurred during the public road demonstration along the driving route. A heatmap visualization is utilized to illustrate the spatial patterns and smoothed distribution of transition events along the route. Events under some driving scenarios were not considered to help isolate the analysis from potential confounding factors, including transitions: 1) below 6.2 mph (10 km/h), to provide a more conservative assessment and focus on more safety-critical scenarios and 2) driving areas before reaching big intersections, due to the lack of traffic light detection and recognition feature as described in Sec. 6.4.

7.1.1 Handover Transitions

Fig. 12.a shows the number and location of HO transitions (i.e., from manual to automated driving mode) that occurred along the route, depicting the areas where the safety driver was confident that the ADS was able to operate in automated driving mode. A total of 35 HO transitions occurred in 13.7 mile (22.1 km) driven in manual mode, having a rate of 2.5 HO/mile (1.5 HO/km) during the public road period. Statistical results about the total manual driving performance, including on urban and suburban roads, are depicted in Table 2.

In urban scenarios, HO transitions occurred frequently after crossing major intersections with traffic lights, indicated by the cyan circles. When the traffic light turned green, the safety driver opted to navigate through the intersections manually. Once the intersection was cleared, the driver would execute the HO transition back to automated mode. This pattern emerged due to an ‘Overly Gradual Acceleration’ in automated mode, which disrupted the normal flow of traffic. Accordingly,

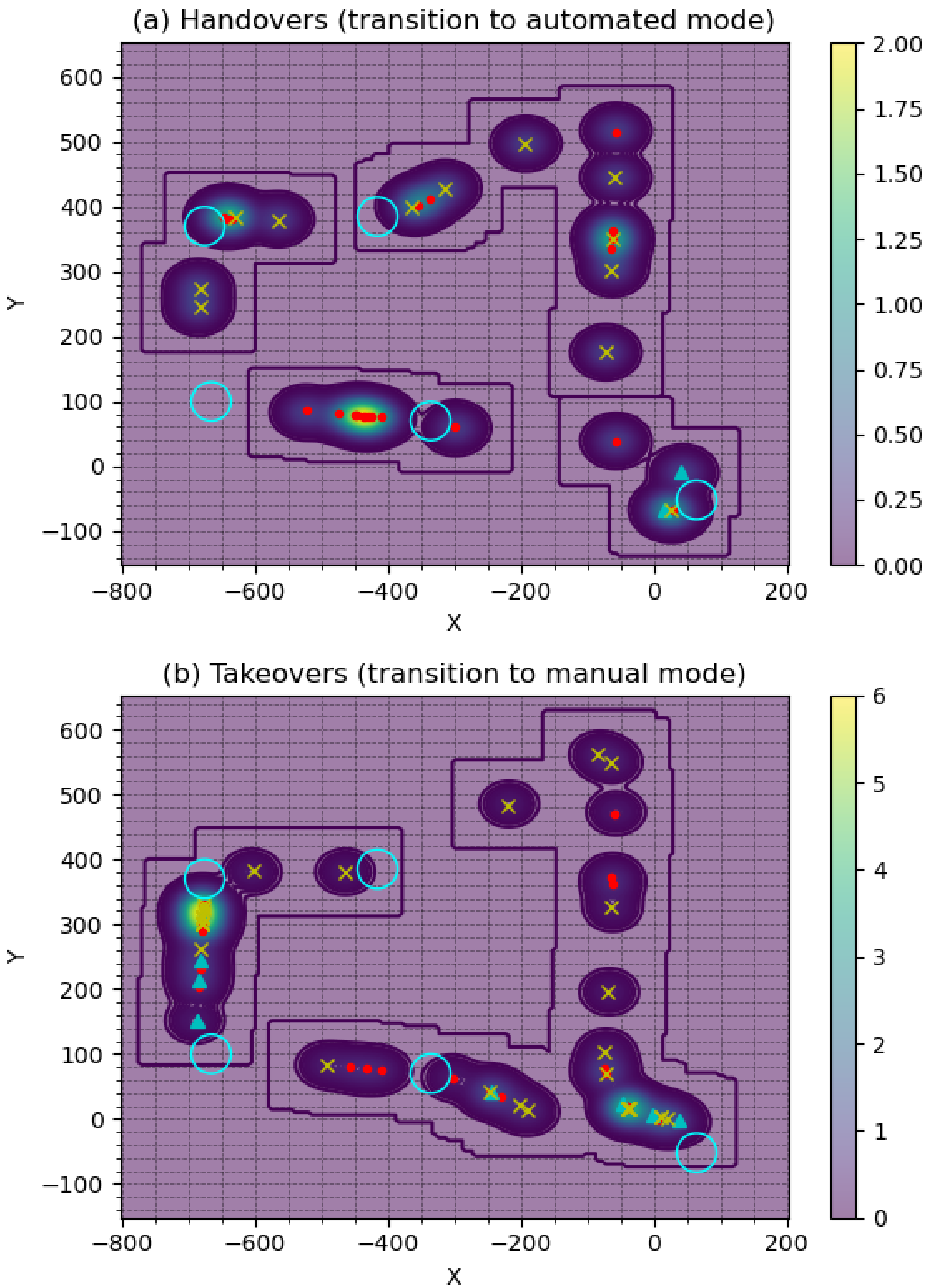


Figure 12. Location of handovers (transitions to automated mode) and takeovers (transitions to manual mode) along the driving route. The frequency of transitions is defined by the color bar placed vertically on the right, having minimum (purple) and maximum (yellow) values. The transitions were obtained from real driving tests using vehicles 1 (red dots), 2 (cyan triangles), and 3 (yellow crosses). The transitions at intersections with traffic lights (cyan circles), as well as the transitions at speeds lower than 3m/s, were not considered.

Table 2. Handover transitions for each Aggie Auto Shuttle. The total (Σ) and mean (μ) estimations for the metrics are denoted with the superscripts + and ∗, respectively.

Road	Metric	Shuttle 1	Shuttle 2	Shuttle 3	Σ^+/μ^*	Unit
urban	**Time**	301.2	32.9	318.3	652.4^+	**min**
	Distance	3.10	1.55	3.29	7.95^+	**mile**
	Handovers (ho)	16	1	8	25^+	**ho**
	Distance per ho	0.19	1.55	0.41	0.31^*	**mile/ho**
	ho per distance	5.16	0.64	2.43	3.14^*	**ho/mile**
suburban	**Time**	400.7	97.9	504.8	1003.4^+	**min**
	Distance	1.43	1.68	2.61	5.71^+	**mile**
	Handovers (ho)	5	1	4	10^+	**ho**
	Distance per ho	0.28	1.68	0.65	0.57^*	**mile/ho**
	ho per distance	3.49	0.59	1.53	1.75^*	**ho/mile**
total	**Time**	701.9	130.8	823.1	1655.7^+	**min**
	Distance	4.56	3.27	5.88	13.73^+	**mile**
	Handovers (ho)	21	2	12	35^+	**ho**
	Distance per ho	0.21	1.63	0.49	0.39^*	**mile/ho**
	ho per distance	4.60	0.61	2.04	2.54^*	**ho/mile**

the safety driver chose to take over manual control temporarily while crossing the intersections.

In suburban areas, HO transitions were infrequent. However, the safety driver often took control when encountering situations related to limitations in the behavioral planning system, mostly caused by requiring manual overtaking maneuvers due to 'Road Obstructions,' and in a minor proportion in other driving scenarios (e.g., 'Objects Near Stop Signs,' 'Oncoming Traffic,' and 'Collision Avoidance'), necessitating manual driving interventions for smoother navigation.

7.1.2 Takeover Transitions

Fig. 12 shows the number and location of TKO transitions (i.e., from automated to manual driving mode) that occurred along the route, illustrating the areas where the safety driver was concerned about the ADS capability to operate safely. A total of 71 TKO transitions occurred in 140 mile (225.1 km) driven in automated mode, having a rate of 0.5 TKO/mile (0.35 TKO/km) during the public road demonstration. Statistical results about the total automated driving performance, including urban and suburban roads, are depicted in Tab. 3.

In both urban and suburban environments, TKO transitions from automated to manual mode predominantly occurred before reaching bus stop zones. In these scenarios, the behavioral planning system assessed potential objects that could conflict with the original path before initiating a 'Pull-Over.' However, if any object was detected close to the planned path, the pull-over maneuver

Table 3. Takeover transitions for each Aggie Auto Shuttle. The total (Σ) and mean (μ) estimations for the metrics are denoted with the superscripts + and ∗, respectively.

Road	Metric	Shuttle 1	Shuttle 2	Shuttle 3	Σ^+/μ^*	Unit
urban	**Time**	172.7	35.3	518.4	241.5^+	**min**
	Distance	27.77	6.96	46.23	80.90^+	**mile**
	Takeovers (tko)	19	5	19	43^+	**tko**
	Distance per tko	1.47	1.40	2.43	1.88^*	**mile/tko**
	tko per distance	0.68	0.71	0.41	0.53^*	**tko/mile**
suburban	**Time**	127.9	28.1	183.4	339.4^+	**min**
	Distance	21.93	4.97	31.93	58.9^+	**km**
	Takeovers (tko)	11	3	14	28^+	**tko**
	Distance per tko	1.99	1.65	2.28	2.1^*	**mile/tko**
	tko per distance	0.50	0.60	0.43	0.47^*	**tko/mile**
total	**Time**	300.6	63.4	493.7	857.8^+	**min**
	Distance	49.71	11.99	78.17	139.87^+	**mile**
	Takeovers (tko)	30	8	33	71^+	**tko**
	Distance per tko	1.65	1.49	2.36	1.97^*	**mile/tko**
	tko per distance	0.60	0.67	0.42	0.50^*	**tko/mile**

was aborted without replanning for an alternative route to the bus stop. Hence, the goal remained on the original path, causing the vehicle to stop and obstruct traffic flow. This issue provoked a necessary intervention of the safety driver through TKO transitions to navigate these situations safely and without disrupting traffic flow.

7.1.3 Takeover Root-cause Analysis

Table 4 summarizes the relevant events that led to takeover (TKO) transitions during the public road demonstration period. The safety drivers gathered this information and documented the relevant events immediately after their occurrence. Subsequently, each TKO transition was analyzed, and the underlying causes were attributed to specific modules within the ADS.

Most takeovers, accounting for 74.9% of the total, were caused by two primary events: 'Pull-Over Maneuver' (55.8%) and 'Road Obstructions' (19.1%). Each one of the remaining 13 identified relevant events played a relatively smaller role, however, contributing to a total of 25% of the takeover events. It can be seen that Shuttle 3 encountered more events and a greater variety of events than Shuttles 1 and 2. This can be attributed to the fact that Shuttle 3 operated in automated mode for a longer duration and covered a greater distance during the pilot period, as evidenced in Tab. 3. A detailed description of each of the relevant events that were encountered during the pilot period is provided next.

Table 4. Relevant events leading to takeovers.

		Urban					Suburban					Total				
		Shuttle			Total		Shuttle			Total		Shuttle			Total	
Module	**Relevant Event**	**1**	**2**	**3**	**#**	**%**	**1**	**2**	**3**	**#**	**%**	**1**	**2**	**3**	**#**	**%**
Perception	Object Boundary			1	1	2.3		1		1	3.6		1	1	2	2.9
Decision	Pull-Over Maneuver	7	5	12	24	55.8						7	5	12	24	35.3
	Oncoming Traffic						2	1	1	4	14.3	2	1	1	4	5.9
	Collision Avoidance	2			2	4.7			2	2	7.1	2		2	4	5.9
	Road Obstruction	1		3	4	9.3	3	1	5	9	32.1	4	1	8	13	19.1
	Object Near Stop Sign						3		2	5	17.9	3		2	5	7.4
	Unexpected Lane Change			1	1	2.3								1	1	1.5
	Emergency Vehicle Interaction			1	1	2.3								1	1	1.5
Control	Inadequate Speed Reduction	3		1	4	9.3						3		1	4	5.9
	Overly Gradual Acceleration	3			3	7.0						3			3	4.4
	Oversteering Issue	2			2	4.7						2			2	2.9
Actuation	Sudden Deactivation								1	1	3.6			1	1	1.5
	HMI Control Loss	1			1	2.3						1			1	1.5
Strategy	Passenger Drop-Off								2	2	7.1			2	2	2.9
	Unexpected Door Opening								1	1	3.6			1	1	1.5

Object Boundary: This event likely occurred when the ADS encountered difficulties in accurately detecting objects near the boundaries of the travel path, potentially leading to unsafe situations that required the safety driver's intervention.

Pull-Over Maneuver: The ADS sometimes struggled to execute safe and appropriate pull-over maneuvers, such as when attempting to pull over to the side of the road. This is mostly due to issues with behavioral planning and object detection, necessitating the safety driver to take control.

Oncoming Traffic: The ADS sometimes was not prepared to respond to vehicles approaching from the opposite driving direction in suburban areas, prompting the safety driver to take over for safer navigation.

Collision Avoidance: The ADS sometimes performed lane departures to avoid potential collisions with vehicles parked too far from the curb, requiring human intervention to prevent crashes.

Road Obstruction: The ADS sometimes was not prepared to respond to obstructions on the road, such as other vehicles parked too far from the curb, leading the safety driver to take control to navigate around these obstacles safely.

Object Near Stop Sign: The ADS sometimes had trouble reacting appropriately when objects were near stop signs, thereby not respecting the stop line to prioritize avoiding a collision with the object, posing a risk of running through the stop sign.

Unexpected Lane Change: The ADS sometimes executed an unexpected lane change to avoid a frontal collision with a vehicle parked on the street, prompting the safety driver to take over to prevent potential crashes or maintain proper lane positioning.

Inadequate Speed Reduction: Sometimes at speeds higher than 30 km/h, the ADS failed to reduce speed adequately, posing a risk of frontal collision or other safety issues, requiring the safety driver to take control and adjust the speed of the vehicle appropriately.

Overly Gradual Acceleration: At intersections, the ADS sometimes accelerated too gradually after handovers due to green lights, potentially disrupting the flow of traffic or causing other safety concerns, leading the safety driver to take over and accelerate more appropriately.

Oversteering Issue: The ADS sometimes experienced oversteering issues, causing the vehicle to veer off course or become unstable, necessitating human intervention to regain control and maintain a safe trajectory.

Sudden Deactivation: The ADS sometimes unexpectedly deactivated or disengaged, requiring the safety driver to take immediate control of the vehicle to ensure safe operation.

Human Machine Interface (HMI) Control Loss: The ADS sometimes experienced issues with the HMI while the vehicle was in motion, potentially causing loss of control or functionality, prompting the safety driver to take over manual control.

Passenger Drop-Off: In certain situations, some passengers asked suddenly to be dropped off at stops other than planned drop-off points, leading the safety driver to intervene and take control to complete the drop-off process.

Unexpected Door Opening: Sometimes, a passenger unexpectedly opened a door while the vehicle was in motion, posing a safety risk and requiring the safety driver to take immediate control to prevent potential crashes.

Most of these technical issues can be resolved with reasonable effort on fine-tuning and calibrating the sensing and control systems of the shuttles with the exception of “Oncoming Traffic” or “Road Obstruction”. This indeed requires lane sharing in suburban roads which is a very complex driving behavior and is difficult to be handled by AVs in a mix AV-HDV setting.

7.2 Other Technical Insights and Experiences

7.2.1 Mapping

The Aggie Auto Shuttles deployment required the creation of a digital model of the driving scenario. This process involved mapping the open roads. However, mapping open roads is a manual process requiring a more complex and time-consuming practice compared to controlled environments.

The initial data collection involved a manual drive, occasionally reaching the top speed of 25 mph (40 km/h) to avoid significantly disrupting normal traffic flow on urban roads with speed limits of 35 mph (56 km/h) in some areas. The resulting 3D point cloud data (PCD) map required extensive manual editing using CloudCompare[1] to remove dynamic objects like vehicles, bicycles, and pedestrians. Including driving rules like posted speed limits, crosswalks, road shoulders, and stop lines necessitated the inclusion of semantic information in the Lanelet2 map format. With the PCD and Lanelet2 maps prepared, the shuttles were ready for their first automated driving ride. However, the manual adaptation process of the virtual scenario model continued iteratively, whereby the research team refined the maps until their quality was appropriate for deployment.

The deployment of vehicles on new routes is currently a complex and resource-intensive process. There is a pressing need for automated processes to create virtual driving environments by seamlessly integrating algorithms that can: 1) detect and remove dynamic objects from PCD maps, 2) accurately map lane boundaries and other road markings, and 3) generate Lanelet2 maps incorporating driving rules, traffic signs, and semantic information. Automating these interconnected tasks would streamline the creation of virtual environments, reducing manual effort and resources, and thereby improving the efficiency and scalability of ADS for rapid expansion into new areas.

7.2.2 Localization

The shuttles primarily relied on LiDAR sensors for geolocalization. The positions of fixed objects within the line of sight were compared with their recorded positions, enabling the vehicles to maintain their intended trajectories across various driving scenarios. Moreover, even in rural forested environments with fewer large static structures, accurate localization could be achieved by using the trunks of trees as reference points for the LiDAR sensors and disregarding continuously changing foliage density across different seasons. No significant deviations from the center of the lane were observed in any of the driving scenarios by the safety drivers.

7.2.3 Object Recognition

The shuttles primarily relied on LiDAR sensors for object recognition, an approach that generally performed well in detecting both dynamic and static objects. However, certain deficiencies were observed by the safety drivers. Firstly, although VLP-16 LiDAR sensors were strategically positioned to cover blind spots, their low spatial resolution hindered the recognition of distant objects, becoming particularly problematic when driving above 19 mph (30 km/h). Secondly, the LiDAR sensors struggled to detect dark objects due to the absorption of the laser signal, potentially leading to missed detection of obstacles and rear-end collisions. Additionally, the size of parked vehicles on the street was sometimes overestimated, causing them to be misinterpreted as obstacles in the travel lane of the shuttle. To address these limitations, the research team proposed the replacement of existing LiDAR sensors with higher-resolution alternatives and with camera and

[1] Source: https://www.danielgm.net/cc/

RaDAR sensors integration into the object recognition system, leveraging the strengths of each sensor type to enhance overall accuracy and reliability. Accurate extrinsic calibration between the LiDAR, camera, and RaDAR sensors is crucial to ensure proper sensor fusion and reliable object detection and tracking across all sensor modalities.

7.2.4 Motion Planning

The shuttles demonstrated reliable performance in handling driving maneuvers at low speeds, aligning with the partial driving automation expectations set for the pilot program. However, the shuttles exhibited some limitations at moderate speeds. The shuttles could stop reliably in front of static and dynamic obstacles when traveling at low speeds but struggled to handle obstacles at speeds exceeding 19 mph (30 km/h) due to the previously described limitations in object recognition. Furthermore, the ADS had difficulty appropriately reacting to road obstructions, such as vehicles parked too far from the sidewalks, or avoiding oncoming traffic, a common scenario on suburban reversible roads. In such cases, the safety driver had to take control of the driving task to ensure safe operation.

During the pilot period, several unanticipated operational scenarios emerged that were not accounted for in the controlled driving environment validation procedures, thereby constituting edge cases. For example, the presence of parked vehicles preceding the designated pull-over area impacted the behavioral system, resulting in the abortion of the pull-over maneuver execution, which requires improvement of the pull-over behavior of the vehicles for future pilot programs. Analogously, an unexpected and unnecessary lane change occurred on an urban thoroughfare to avoid collision with a parked vehicle, necessitating the intervention of the safety driver to take control of the shuttle, requiring more testing and validation on events triggering lane change maneuvers. These issues could be ameliorated by modifying the behavioral parameters that trigger and govern such actions. Additionally, the presence of emergency vehicles, such as ambulances and fire trucks, in the proximal environment prompted the safety driver to assume control of the driving task to yield the right of way, as this behavior exceeded the scope of the functionalities expected in the public road demonstration.

7.2.5 Motion Tracking

Similar to the motion planning aspect, the shuttles demonstrated reliable performance in handling driving maneuvers at low speeds. However, their performance under moderate speeds sometimes necessitated intervention from safety drivers. One such scenario arose at intersections with traffic lights, where a handover maneuver was required after the traffic light changed from red to green. In these situations, the overly gradual acceleration designed for the shuttles to prioritize passenger comfort conflicted with the traffic flow, prompting the safety driver to accelerate manually. This behavior could be improved by employing a less conservative parameter for accelerations, while still adhering to safety values for longitudinal accelerations. Furthermore, the performance of takeovers at moderate speeds required a delicate procedure of positioning the vehicle near the center of the planned path to avoid aggressive steering actions during the transition from manual to automated driving.

7.3 Intersection Handling

The research team has invested significant effort in solving the problem of handling intersections using onboard sensors, particularly cameras. However, their approach did not provide reliable traffic light detection due to sensitivity to environmental noise, such as glare and varying lighting conditions. A more reliable approach would be to use V2I communication. The research team will continue working with City of Greensboro to upgrade the traffic light signals to enable V2I communication for potential future pilot projects.

8 User's Feedback

Dr. Marada McBride assisted with designing and instrumenting questionnaires and obtaining IRB approvals to survey passengers and capture their opinions on the deployment of Aggie Auto Shuttles including:

- Pre-ride (before riding with the Aggie Auto Shuttles.)
- Post-ride survey (an email was sent to registered participants who completed the pre-ride survey)

A QR code was provided at stops and inside the vehicles. While an in-depth analysis of the survey results is underway, the preliminary results are presented in Figures 13 and 14.

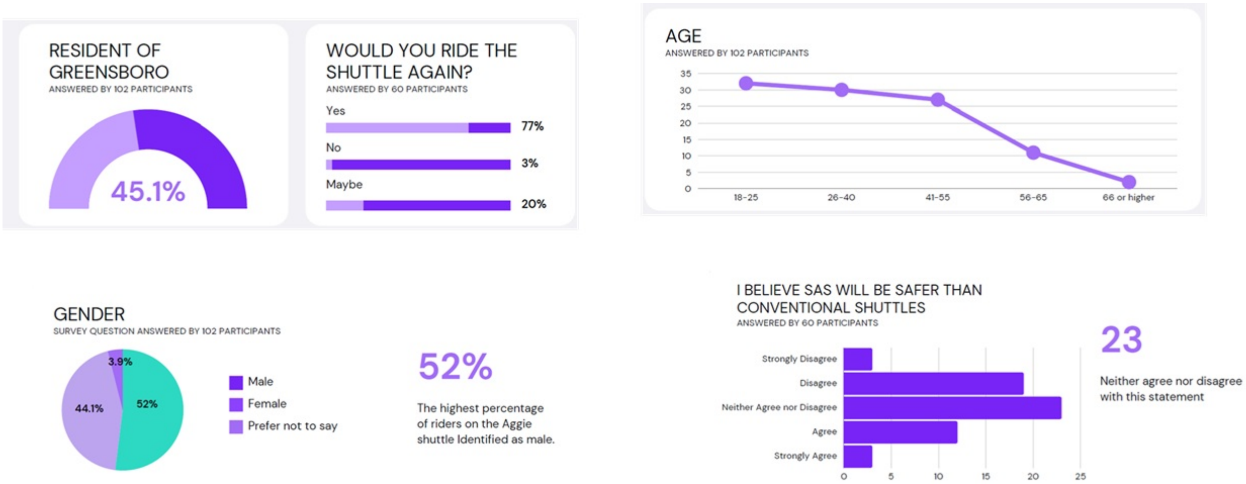


Figure 13. Pre-ride survey results for Aggie Auto Shuttles pilot program.

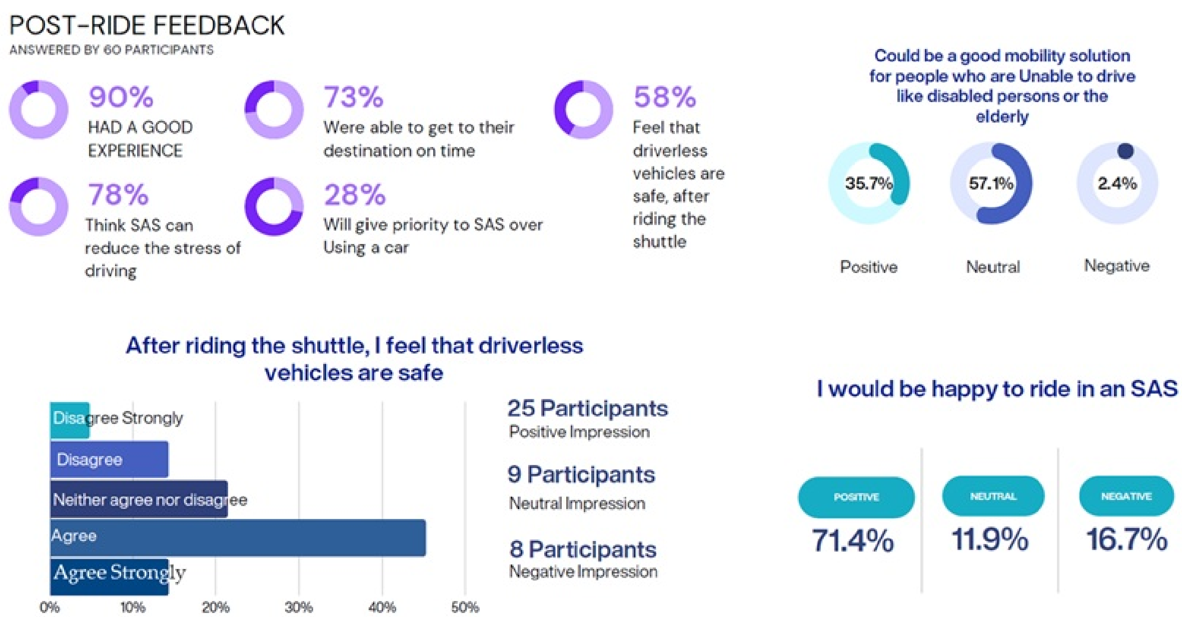


Figure 14. Post-ride survey results for Aggie Auto Shuttles pilot program.

9 Conclusion

The Aggie Auto Shuttles pilot project served as a critical exploration of the feasibility and effectiveness of automated shuttles in public transportation. The project successfully demonstrated that automated shuttles equipped with advanced sensing technologies can navigate both urban and suburban environments, providing valuable insights into their operational capabilities, challenges, and user experience. The deployment of these shuttles on public roads provided crucial real-world data that helped assess the strengths and limitations of current automated driving systems.

The funding for this project played a crucial role in supporting a wide range of activities necessary for the successful evaluation and deployment of automated shuttles. It enabled the modification of Aggie Auto Shuttles to equip them with advanced automated driving system (ADS) technology, integrating LiDAR, cameras, radar, and computing hardware. Additionally, through this project, the research team enhanced the software components of Aggie Auto Shuttles, including localization, mapping, and route planning to allow their deployment on public roads. The project benefited from extensive testing in both controlled environments and real-world conditions, ensuring a comprehensive assessment of the shuttles' capabilities and limitations.

Beyond technical development, the funding facilitated pilot program operations such as vehicle maintenance, data collection, and performance evaluation. Public outreach efforts—including stakeholder engagement, passenger surveys, and educational events—were also supported to increase awareness and build public trust in automated vehicle technology. Furthermore, the project contributed to workforce development, equipping faculty, graduate students, and engineers with expertise in system integration, safety assessments, and data analysis. This investment has positioned the research team to refine and expand their automated shuttle testbed for future pilot projects, further advancing the adoption of autonomous vehicle technology in public transportation.

The pilot also highlighted challenges associated with automated shuttle deployment, including handling unpredictable traffic conditions, navigating shared roadways, and responding to complex urban scenarios such as signalized intersections and oncoming traffic within a single lane. Additionally, while pedestrian detection was well-integrated, future implementations must improve interactions with other vulnerable road users such as cyclists and e-scooter riders. These insights underscore the importance of continued research into sensor fusion improvements, Vehicle-to-Infrastructure (V2I) communication, and more advanced route optimization to further enhance shuttle performance.

Beyond the technical findings, the project played a significant role in increasing public awareness and acceptance of automated vehicle technology. By allowing community members to experience automated shuttles firsthand, the pilot fostered greater understanding of the technology's capabilities, limitations, and safety measures. Public engagement through surveys and outreach efforts provided valuable feedback that can inform future deployments and help build public trust in autonomous transit solutions.

Given these findings, it is recommended that NCDOT and other transportation agencies continue supporting research and pilot expansions before transitioning to full-scale deployment of automated shuttles in regular transit operations. Future trials should focus on overcoming operational challenges, refining vehicle response mechanisms, and ensuring seamless multimodal integration with existing transit networks. Continued collaboration with policymakers, industry partners, and local communities will be essential in refining the technology and expanding its applications to serve a wider range of transportation needs.

By implementing these improvements, North Carolina can position itself as a leader in the adoption of safe, efficient, and inclusive automated transit systems, ultimately enhancing mobility options across North Carolina.

9.1 Future Plan

Moving forward, the research team aims to build on the insights gained from this project to further advance automated shuttle technology and its practical applications. The following key initiatives outline the next steps:

- Enhancing Pilot Programs with V2I Technology: Future pilots will incorporate V2I communication to improve the automated shuttles' ability to navigate intersections with minimal intervention from the safety driver. Conversations have already begun with the City of Greensboro to upgrade traffic signals to support V2I communication, laying the groundwork for more advanced automated transit operations for potential future pilot projects.
- Elevating Automation Levels: The team is actively pursuing the goal of eliminating the need for an onboard safety driver by exploring remote operation capabilities. A follow-up Technology Transfer grant has been provided to the team to investigate remote supervision mechanisms, ensuring that while a safety driver is not physically onboard, a fallback option remains available through remote operation technology.
- Expanding to Rural Deployment: Recognizing the potential impact of automated shuttles in rural areas, the research team is exploring future pilot programs to assess the technology's robustness across diverse terrains and traffic conditions. A pilot initiative in a rural North Carolina community is under consideration to evaluate the feasibility and benefits of automated microtransit solutions in rural regions.

9.2 Recommendations

To further enhance the success and scalability of automated shuttle services in North Carolina, the following recommendations are proposed based on the outcomes of this pilot project:

- **Improving Traffic Signal Communication:** Future pilot programs should collaborate with local agencies to integrate Vehicle-to-Infrastructure (V2I) communication at traffic signals. This technology will allow shuttles to receive real-time traffic light data, improving efficiency and safety at intersections.
- **Expanding Services to Rural and Underserved Communities:** Given the success of the Greensboro pilot project, future deployments should focus on providing transportation options in more diverse scenarios, such as rural and low-density areas where automated microtransit services could play a significant role in addressing transportation challenges. These communities often lack access to reliable public transit, and automated shuttles can offer a flexible and cost-effective solution.
- **Enhancing User Experience:** To build public trust and encourage ridership, user-friendly ride-booking apps, real-time vehicle tracking, and accessible passenger feedback channels should be implemented to facilitate the adoption of these services.
- **Strengthening Public Education Campaigns:** While the Aggie Auto Shuttle service was a success, ridership could have been further increased if a public awareness campaign had been initiated earlier through multiple channels and community partnerships. Such campaigns are essential for increasing public awareness, engagement, and acceptance of automated shuttle technology.
- **Continuing Pilot Projects for Full Adoption of AV Technologies:** Pilot projects should continue with specific use cases to gradually transition toward full adoption of automated vehicle technologies. Ongoing testing and phased deployments will help identify limitations, prepare infrastructure, and increase public awareness and acceptance. These pilots will also provide critical insights into operational challenges and best practices for broader implementation.
- **Integrating Automated Shuttles with Multimodal Transportation Networks:** To maximize efficiency and expand the reach of public transit, automated shuttles could be integrated into existing multimodal transportation systems. Pilot project with a focus on multi-modal integration of automated shuttles will help assess the challenges and opportunities. This

includes pilot projects connecting shuttles to bus networks, train stations, and airports, allowing for smooth transfers between different modes of transportation. Such integration will enhance accessibility, reduce transit gaps, and improve the overall effectiveness of public transportation services.

By adopting these recommendations, NCDOT can continue leading the way in advancing automated transit solutions, improving mobility options for communities across North Carolina.

References

[1] K. Coyner, S. Blackmer, J. Good, P. Lewis, and A. Grossman, "Low-speed automated vehicles (lsavs) in public transportation," Tech. Rep., 2021.

[2] P. Pokorny, B. Skender, T. Bjørnskau, and M. P. Hagenzieker, "Video observation of encounters between the automated shuttles and other traffic participants along an approach to right-hand priority t-intersection," *European transport research review*, vol. 13, pp. 1–13, 2021.

[3] T. Menzel, G. Bagschik, and M. Maurer, "Scenarios for development, test and validation of automated vehicles," in *2018 IEEE Intelligent Vehicles Symposium (IV)*. IEEE, 2018, pp. 1821–1827.

[4] S. Klauer, Y. Hong, M. Mollenhauer, and J. P. T. Vilela, "Infrastructure-based performance evaluation for low-speed automated vehicle (lsav)," *Safety*, vol. 9, no. 2, p. 30, 2023.

[5] M. M. Nesheli, L. Li, M. Palm, and A. Shalaby, "Driverless shuttle pilots: Lessons for automated transit technology deployment," *Case studies on transport policy*, vol. 9, no. 2, pp. 723–742, 2021.

[6] I. Zubin, N. Van Oort, A. Van Binsbergen, and B. Van Arem, "Deployment scenarios for first/last-mile operations with driverless shuttles based on literature review and stakeholder survey," *IEEE Open Journal of Intelligent Transportation Systems*, vol. 2, pp. 322–337, 2021.

[7] A. Madridano, S. Campos, J. M. Perez, A. Valle, D. Martín, R. A. Lattarulo, M. Á. de Miguel, C. Sierra, J. Del Olmo, C. O. Chacón *et al.*, "Evolution of bus shuttle service in madrid towards autonomous operation, a practical use case," in *2023 IEEE 26th International Conference on Intelligent Transportation Systems (ITSC)*. IEEE, 2023, pp. 2698–2704.

[8] Y. Li, J. Ni, and J. Hu, "Overall architecture and system design of shuttle unmanned ground vehicle with road verification in intelligent transportation system zone," *IET Intelligent Transport Systems*, vol. 17, no. 7, pp. 1275–1287, 2023.

[9] L. Sherry, J. Shortle, G. Donohue, B. Berlin, and J. West, “Autonomous systems design, testing, and deployment: Lessons learned from the deployment of an autonomous shuttle bus,” in *2020 Integrated Communications Navigation and Surveillance Conference (ICNS)*. IEEE, 2020, pp. 5D1–1.

[10] M. M. Islam, A. A. R. Newaz, L. Song, B. Lartey, S.-C. Lin, W. Fan, A. Hajbabaie, M. A. Khan, A. Partovi, T. Phuapaiboon, A. Karimoddini, and A. Homaifar, “Connected autonomous vehicles: State of practice,” *Applied Stochastic Models in Business and Industry*, vol. 39, no. 5, pp. 684–700, 2023.

[11] A. M. Haque and C. Brakewood, “A synthesis and comparison of american automated shuttle pilot projects,” *Case Studies on Transport Policy*, vol. 8, no. 3, pp. 928–937, 2020.

[12] J. Godoy, J. Pérez, E. Onieva, J. Villagrá, V. Milanés, and R. Haber, “A driverless vehicle demonstration on motorways and in urban environments,” *Transport*, vol. 30, no. 3, pp. 253–263, 2015.

[13] A. Broggi, P. Cerri, S. Debattisti, M. C. Laghi, P. Medici, D. Molinari, M. Panciroli, and A. Prioletti, “Proud—public road urban driverless-car test,” *IEEE Transactions on Intelligent Transportation Systems*, vol. 16, no. 6, pp. 3508–3519, 2015.

[14] T. De Ceunynck, B. Pelssers, T. Bjørnskau, O. Aasvik, A. Fyhri, A. Laureshyn, C. Johnsson, M. Hagenzieker, and H. Martensen, “Interact or counteract? behavioural observation of interactions between vulnerable road users and automated shuttles in oslo, norway,” *Traffic safety research*, vol. 2, p. 000008, 2022.

[15] H. Villadsen, D. B. Lanng, and I. Hougaard, “Automated shuttles and ‘negotiation in motion’–a qualitative meta-synthesis of spatial interactions with human road users,” *Transport Policy*, vol. 137, pp. 23–31, 2023.

[16] T. Shan, B. Englot, D. Meyers, W. Wang, C. Ratti, and R. Daniela, “Lio-sam: Tightly-coupled lidar inertial odometry via smoothing and mapping,” in *IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. IEEE, 2020, pp. 5135–5142.

[17] F. Poggenhans, J.-H. Pauls, J. Janosovits, S. Orf, M. Naumann, F. Kuhnt, and M. Mayr, “Lanelet2: A high-definition map framework for the future of automated driving,” in *Proc. IEEE Intell. Trans. Syst. Conf.*, Hawaii, USA, November 2018. [Online]. Available: http://www.mrt.kit.edu/z/publ/download/2018/Poggenhans2018Lanelet2.pdf

[18] J. Saarinen, H. Andreasson, T. Stoyanov, and A. J. Lilienthal, "Normal distributions transform monte-carlo localization (ndt-mcl)," in *2013 IEEE/RSJ international conference on intelligent robots and systems*. IEEE, 2013, pp. 382–389.

[19] K. Aoki, T. Sato, E. Takeuchi, Y. Ninomiya, and J. Meguro, "Error covariance estimation of 3d point cloud registration considering surrounding environment," *Journal of Robotics and Mechatronics*, vol. 35, no. 2, pp. 435–444, 2023.

[20] J. Matute, M. Rodriguez-Arozamena, J. Perez, and A. Karimoddini, "Sensor fusion-based localization framework for autonomous vehicles in rural forested environments," in *2023 IEEE 26th International Conference on Intelligent Transportation Systems (ITSC)*, 2023, pp. 1007–1013.

[21] T. Yin, X. Zhou, and P. Krähenbühl, "Center-based 3d object detection and tracking," *CVPR*, 2021.

[22] A. H. Lang, S. Vora, H. Caesar, L. Zhou, J. Yang, and O. Beijbom, "Pointpillars: Fast encoders for object detection from point clouds," in *Proceedings of the IEEE/CVF conference on computer vision and pattern recognition*, 2019, pp. 12 697–12 705.

[23] J. Matute, S. Diaz, and A. Karimoddini, "Sliding mode control for robust path tracking of automated vehicles in rural environments," *IEEE Open Journal of Vehicular Technology*, vol. 5, pp. 1314–1325, 2024.

[24] M. Azage, J. Matute, and A. Karimoddini, "Learning from human driver demonstration for speed control of ground autonomous vehicles," in *2024 IEEE 19th Conference on Industrial Electronics and Applications (ICIEA)*. IEEE, 2024, pp. 1–8.

[25] North Carolina Department of Transportation, "On-demand microtransit," 2023, accessed: 2025-02-23. [Online]. Available: https://www.ncdot.gov/divisions/integrated-mobility/public-transit-services/on-demand-microtransit/Pages/default.aspx

[26] North Carolina Department of Transportation, Integrated Mobility Division, "Ncdot on-demand microtransit annual report," North Carolina Department of Transportation, Tech. Rep., 2023, accessed: 2025-02-23. [Online]. Available: https://www.ncdot.gov/divisions/integrated-mobility/public-transit-services/on-demand-microtransit/Documents/ncdot-on-demand-microtransit-annual-report.pdf