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CAPMETRO ADS YARD AUTOMATION RESEARCH AND DEPLOYMENT: PHASE ONE

FINAL REPORT

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Table of Contents

LIST OF FIGURES

LIST OF TABLES

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Clever Devices, Perrone Robotics, Inc., Texas A&M Transportation Institute, WSP, and ChargeSim.

CapMetro also offers the utmost appreciation to the many CapMetro staff—directors, project managers, IT specialists, maintenance staff, and drivers—without whom this project would not have come to a successful conclusion.

ABSTRACT

This report presents the outcomes and insights from the CapMetro Yard Automation Research Development (YARD) Phase One project, funded by the Federal Transit Administration (FTA) under the Advanced Driver Assistance Systems (ADAS) for Transit Buses Demonstration and Automated Transit Bus Maintenance and Yard Operations Demonstration program. The project evaluated the feasibility, benefits and challenges for buses equipped with SAE Level Automated Driving Systems (ADS) in a real-world transit bus depot environment. The automated bus yard demonstration took place at CapMetro's North Operations bus depot in Austin, Texas. The research, analysis, and demonstration align with the FTA's Strategic Transit Automation Research (STAR) Plan, which seeks to advance automation technologies in public transit to help improve safety, efficiency, and workforce development initiatives.

The CapMetro YARD project focused on four primary goals:

1) Test automated battery electric buses (BEBs) within routine yard maneuvers
2) Share lessons learned with industry stakeholders
3) Assess workforce impacts related to fleet automation
4) Determine the long-term viability of fleet-wide bus yard automation

The project team successfully retrofitted a New Flyer Xcelsior BEB with ADS technology and achieved SAE Level 4 autonomous maneuvers, including automated bus wash navigation, precision parking, remote start/stop, and automated charging. The project team also developed a detailed benefit-cost analysis (BCA) revealing a net present value of $114.1 million and a benefit-cost ratio of 3.25 over a 23-year period, with significant operational, safety, and infrastructure savings.

A key component of the project was the workforce analysis results, led by Texas A&M Transportation Institute (TTI), which examined the impact of automation on various roles within

the bus depot. Initial findings included some positions, such as service island attendants, may see a reduction in labor hours, but new roles such as Yard Hostler(s) and a Yard Supervisor may be required for future automated bus fleets.

The technical implementation involved collaboration between CapMetro, WSP, and Perrone Robotics. The project included two separate AV demonstrations. The first demonstration included an electric SAE Level 4 cutaway vehicle intended to educate CapMetro frontline staff in the early months of the project and capture helpful information such as route mapping data to help inform the larger, more complex demonstration. Once the retrofit phase was completed by PRI in Viriginia where Perrone Robotics is headquartered, the second and final demonstration took place within the North Ops bus depot and utilized an overhead, high-speed Heliox pantograph charger.

In conclusion, Phase One of the CapMetro YARD project demonstrated the practical viability and substantial benefits of automated bus yard operations, providing valuable lessons learned for future demonstrations and deployments. The project's achievements support the FTA's goals of improving safety, promoting American competitiveness, and examining workforce development impacts of automation within the public transit industry.

EXECUTIVE SUMMARY

In June 2023, and the Capital Metropolitan Transportation Authority (CapMetro) was awarded $949,500 through the Federal Transit Administration (FTA) Advanced Driver Assistance Systems (ADAS) for Transit Buses Demonstration and Automated Transit Bus Maintenance and Yard Operations Demonstration Program for the CapMetro ADS Yard Automation Research and Deployment (YARD) project in Austin, Texas. The CapMetro ADS YARD project demonstrated automated driving systems (ADS) technology in multiple vehicles at their North Operations (North Ops) bus depot.

The CapMetro ADS YARD project identified four (4) main goals:

1. Test and assess the potential future benefits and challenges of automated battery-electric buses (BEBs) through routine bus yard maneuvers.
2. Share lessons learned from the automated vehicle demonstrations with CapMetro stakeholders and industry partners to improve the capabilities of automation technology.
3. Collaborate with CapMetro workforce to better understand the potential impacts to current positions supporting yard operations and identify what potential new positions may be required to operate and maintain automated BEBs.
4. Determine the long-term viability of fleet-wide bus yard automation for current and future CapMetro bus depots.

In addition, the CapMetro YARD Phase One Project accomplished the original goals of the FTA ADAS and Bus Maintenance and Yard Operations demonstration program which included the following:

- Improve safety (captured in benefit-cost analysis).
- Promote American competitiveness and economic development (complied with Buy America procurement requirements).
- Support workers and workforce development (deep insights collected from TCRP-sponsored bus automation workforce calculator led by TTI).

PROJECT KEY RESULTS AND LESSONS LEARNED

Due to the planning and coordination led by the CapMetro Project Team, each of the project goals were met and all Phase One testing was successfully completed. This demonstration not only completed SAE Level 4 autonomous maneuvers within an active bus yard, but also successfully demonstrated autonomous charging underneath an overhead pantograph dispenser. The demonstration provided an in-person, realistic view into the potential safety, operational, and energy savings that automation solutions can provide.

A high-level list of the achievements from the CapMetro YARD Project Phase One includes:

- The retrofit of a New Flyer Xcelsior battery-electric bus (BEB) with an Automated Driving System (ADS).
- Achieved a 94.97% and 100% test case pass rating during the two exhaustive test and validation stages (with an operator and without an operator), respectively. (Stage 1 had a deferral rate—tests not able to be completed for various reasons—of 29.7%, and Stage two had a deferral rate of 55.5%. The reasoning for each is expanded upon in the Results Section).
- In-depth testing of automating the bus wash and documenting potential damage to sensors that may inhibit system capabilities. The ADS-equipped BEB completed the bus wash test case with no documented damage and performed the exact same route within the yard post-wash.
- A detailed benefit-cost analysis (BCA) of the retrofit and deployment of 104 automated buses (phased in over 10 years) produced a discounted (3.1%) cost of $50.7 million and a rating of 3.25 when accounting for all capital and operating expenses in comparison to the $164.8 million in realized benefits over 23 years.
- The project enabled real world workforce data and requirements to be applied to the Transit Cooperative Research Program—TCRP—approved automated workforce calculator that used theoretical assumptions. Led by TTI, the analysis concluded the predicted change to 10 different operations and maintenance (O&M) roles within the yard and created two additional roles to support the new ADS technology.

1. INTRODUCTION TO THE CAPMETRO ADS YARD AUTOMATION RESEARCH AND DEPLOYMENT (YARD) PROGRAM IN AUSTIN, TEXAS

Automation capabilities have grown rapidly in recent years and have changed the dialogue around all aspects of the surface transportation system. Transit bus automation could deliver many potential benefits, but transit agencies need additional research and practical information to make informed demonstration and deployment decisions.

In September 2022, the FTA announced a Notice of Funding Opportunity (NOFO) to solicit proposals from organizations interested in advancing research into transit bus automation through demonstrations of Advanced Driver Assistance Systems (ADAS) and automation of bus movements in transit bus yards. CapMetro, interested in understanding the impacts of automation technology, including yard operations and how that would affect current positions and operating and maintaining vehicles, applied for funding. In June 2023, CapMetro was awarded $949,500 for the CapMetro ADS Yard Automation Research and Deployment (YARD) Program in Austin, Texas.

Now in 2025, CapMetro intends to continue their mission to be one of the most innovative transit agencies in North America and lead the first-ever zero-emission automated bus depot demonstration by leveraging the FTA Automated Transit Bus Maintenance and Yard Operations Demonstration Program (the Project). CapMetro is committed not only to advancing the capabilities of its fleet through this strategic opportunity, but also to using the agency's leadership in this emerging area to cooperatively provide experience, insights, and lessons learned to the broader transit community. This grant-funded project is the first phase of a two-phase programmatic effort to successfully demonstrate the first automated bus yard in the United States.

The CapMetro YARD demonstration took place at the North Ops bus depot, which is located at 9315 McNeil Rd, Austin TX 78758. The project team has included an aerial image below that illustrates where the demonstration took place, Figure 1-1. The project team selected the North Ops bus depot for this demonstration due to the planned overhead pantograph charging dispenser that was to be installed, which was critical to prove how a BEB fleet can autonomously charge.

Figure 1-1: An aerial photograph of CapMetro's North Operations bus depot

In general, the bus fleet mix of CapMetro includes 104 BEBs and 375 diesel buses. As of September 2025, CapMetro has installed 13 plug-in chargers, 1 overhead 360kW high-speed charger—Figure 1-2—and 90 overhead pantograph dispensers that are connected to 30 180kW Heliox chargers at the North Ops bus depot. Concerning future considerations for autonomous technology, CapMetro is interested in further collaborating with major bus OEMs to explore adding ADAS capabilities to future bus specifications as a near-term step to future yard automation capabilities. CapMetro believes there are clear safety, reliability, and efficiency benefits to be realized through ADAS and ADS technologies.

Figure 1-2: The project team observes the bus charging via overhead pantograph after an automated approach

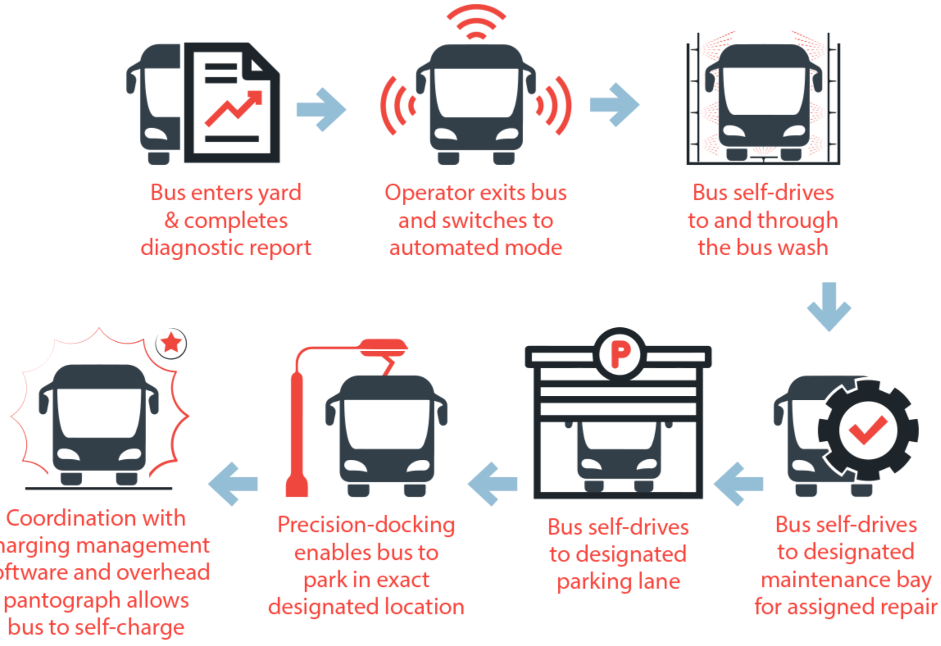
PURPOSE OF THE PROJECT

The YARD project tested automation technologies in CapMetro's North Operations (North Ops) bus depot. For the bus yard research and deployment effort, it was important that the proposed projects included a physical demonstration of a Level 4 automated bus within an active bus yard to assess the potential day-to-day challenges of mixing automated buses with non-automated buses and furthermore, what the future may look like as a completely zero-emission and automated fleet within a bus yard.

AUTOMATED USE CASES

The core benefits for bus yard automation include capacity savings, infrastructure reduction, an increase in safety, and time reduction for operations and maintenance personnel. These benefits are achievable in higher forms of vehicle automation because the vehicle maneuvers are repeated daily, during pull-in and pull-out, Figure 1-3, and at restricted speeds. Additionally, the bus yard is an ideal setting for testing automation technology due to the restricted public access. Below is a specific list of use cases, highlighted by supporting maneuvers, that were demonstrated through this project.

Figure 1-3: Order of Events When a Bus Returns from Service in an Automated Yard



AUTOMATED BUS WASH NAVIGATION

The bus wash maneuver in the context of yard automation focuses on decreasing the requirement for maintenance personnel to drive the vehicle through the exterior cleaning wash bay. With the technology that is available on the market today, automating interior cleaning of a bus is not possible. However, while most transit agencies already have automated bus wash systems, by having a Level 4 automated bus, the time spent driving the bus to the assigned wash bay and then driving it from the wash bay to its assigned parking lane, is time that can be repurposed.

AUTOMATED PRECISION PARKING

Precision parking can be a form of ADAS or ADS solutions and involves consistently stopping at an exact location and orientation. Level of accuracy is typically measured in centimeters and within the yard, and can be used for automated charging, bus wash navigation, and general navigation. Some of the known challenges that can impact precision-docking can be low or minimal GPS signal connectivity, braking modulation, and object misdetection via sensors.

REMOTE START AND STOP

The remote start maneuver is the response to a request of the automated bus starting remotely from a software program that enables the automated bus to complete its planned mission within the bus yard. The remote start capability is a key feature to achieve time savings by reducing the distance operators need to walk during pre- and post-trip. In order for fleet automation to be scalable, remote start will need to align with pull-out schedules and be controlled through a software program that is integrated with the transit agency's scheduling system.

AUTOMATED CHARGING

The Automated Charging maneuver is very similar to the Precision Parking Maneuver; however, this maneuver explicitly requires alignment with an overhead pantograph dispenser. The pantographs have a usable tolerance of 6-12 centimeters so the parking must be very specific. Additionally, this is the only maneuver on the list which also relies on technology from another vendor. After parking, the vehicle must be able to connect digitally to the charging system and request that the pantograph be deployed for charging. Automating this entire process saves time spent manually aligning the bus with the charging rails, which, depending on the scenario, can be quite difficult to accomplish manually.

2. PROJECT PARTNERS

CAPMETRO

CapMetro is the public transportation provider for the greater Austin, TX region; operating bus (MetroBus, MetroExpress, and MetroRapid), paratransit services, and a commuter rail system. CapMetro serves both Travis and Williamson counties. In November 2020, Project Connect was approved to build one new light rail line, one new BRT line, and one new commuter rail line, while expanding MetroRapid bus routes.

WSP

WSP provides strategic, technical, and operational guidance across connected, automated, and electric vehicle technologies. WSP also led pilot testing, technology development, and advised on policies, and plans to support successful implementation.

CLEVER DEVICES

Clever Devices' primary role is to provide the user interface and operations management software for the bus yard. Clever Devices has extensive experience, credentials and a strong foundation proving Yard Management through their SmartYard solution. Their existing SmartYard application is the industry's most advanced technology solution to monitor and improve workflow in the depot, used on thousands of buses in North America.

TEXAS A&M TRANSPORTATION INSTITUTE

The Texas A&M Transportation Institute (TTI) is an agency of the State of Texas and member of The Texas A&M University System. For 70 years, TTI has addressed complex transportation challenges and opportunities with innovation, objectivity, and unmatched technical expertise. TTI provides expertise in all aspects of public transportation planning, management, and operations; and delivers practical, data-driven, innovative, person-centered solutions to improve accessibility, equity, efficiency, effectiveness, and safety of public transportation through research, education, and technology transfer.

PERRONE ROBOTICS, INC.

Perrone Robotics, Inc. (PRI) is a leading provider of fully autonomous vehicle systems. The company delivers mobility excellence via their automation kit TONY® (short for "To Navigate You"). With over 17 years and 200 person-years of experience, 40,000 AV miles travelled, and over 30 different vehicles powered by their software, PRI knows what it takes to successfully control a vehicle. PRI has built this science and expertise into the TONY retrofit kit, a vehicle agnostic approach to autonomous transit.

3. PROJECT MANAGEMENT- WSP

SCOPE

As the Project Implementation Lead, WSP USA served as the central coordinating entity for CapMetro's ADS YARD project. WSP USA developed and refined the following major deliverables:

- The Concept of Operations (CONOPS) detailed the relationships between the Project Team, stakeholders, users, and the technology for each of the two demonstrations.
- The Data Management Plan (DMP) documented the information flow between existing systems of record at CapMetro and systems new to the project. The DMP will encompass information such as the type of data collected, data structure, data schema, data volume, variety, and calibration, ultimately supporting a data analytics system for reporting KPIs.
- The Benefit-Cost Analysis (BCA) identified and calculated potential benefits specific to automated BEBs, validated as part of the YARD Program demonstrations. Implementation lead will also include costs from AV retrofit partner, CapMetro, and other sources.
- The Test Plan defined the procedures, objectives, and methodology of the CapMetro YARD Demonstration Two Testing, including:
    - Notify project stakeholders of the testing goals and performance expectations of the automated BEB during Demonstration Two
    - Define the test methodology and defect management procedures that will be used during Demonstration Two.
    - Create a clear and concise guide for how Perrone Robotics, the YARD automation lead, should structure and manage the deployment at the North Operations bus depot.
    - Develop an industry first, standardized test plan template that other transit agencies can follow to ensure their future automated bus fleets are reliable, safe, and efficient.
- The Safety Plan highlighted the protocols and steps taken during the YARD deployment to address the risks associated with an AV deployment and ensure the safety of all

participants including the CapMetro employees working in and around the deployment area

- The Capacity Analysis was developed by ChargeSim in association with WSP. ChargeSim created optimized, automated yard parking layouts which showed the space and organizational benefits of using automation. They also ran charging simulations which showed daily yard movement based on real world CapMetro metrics such as the fleet quantity, BEB battery size, charging time, and active service schedules.
- FTA reporting produced quarterly progress reports and a final report that summarizes key lessons learned and recommendations for Phase Two.

WSP USA's scope further encompasses the proactive development and maintenance of a detailed project schedule to ensure alignment among CapMetro stakeholders and all technical partners. WSP USA manages federal and local match funding across program management, data integration, and reporting tasks. Additionally, WSP supports the implementation efforts within the various CapMetro departments (operations, maintenance, safety, IT, etc.) to ensure stakeholders are actively involved and aware of the project plans.

PROJECT MANAGEMENT PLAN

The Project Management Plan (PMP) served as the guide for executing Phase One of the ADS YARD project. The PMP defined the detailed Statement of Work, breaking the program into four core tasks: Project Management, Automated Vehicle Demonstrations, Bus Automation Workforce Analysis, and Software Architecture Schematic, which also ties each to specific deliverables. The schedule spans a period of performance from December 2023 through May 2025 and allocates the $1,261,800 total grant and match funding across personnel, demonstrations, analysis, and software development. The PMP also outlines Quality Management and CapMetro's approach to Scope, Schedule, and Budget Management. Any proposed scope changes, budget variances, or schedule revisions are carefully evaluated and recorded through the Configuration Control process.

The Project Team's organizational management and staffing plan clarify that the Implementation Lead reports directly to CapMetro and provides programmatic oversight to the AV retrofit, workforce analysis, and fleet-dispatch software partners. The PMP highlights communications, reporting, and deliverable acceptance, including a mix of remote and in-person forums (kickoff, bi-weekly status, monthly FTA, and ad-hoc workshops) to ensure transparent stakeholder engagement.

DATA MANAGEMENT PLAN

The Data Management Plan (DMP) described how digital information will be created, used, shared, and preserved during, and after the project.

OVERVIEW OF DIGITAL DATASETS

The digital datasets include new data streams produced by the automated vehicle, inputs and outputs for the technical deliverables, and additional streams that are expected to come online in subsequent phases.

The first grouping, new data streams produced by the automated vehicle, captures everything generated directly by PRI based on the outputs from the automated-vehicle platform during the two Phase One demonstrations. Perrone Robotics Inc (PRI) will supply interpreted and visualized data from the lidar, radar and cameras, pulled from the vehicle's on-board systems in the form of "event summaries." These event summaries are interpreted data that will explain why test cases resulted in failures or otherwise interesting scenarios. In addition, WSP will provide the full test case spreadsheets including planned testing, results, and test engineer comments.

Inputs and outputs for the technical deliverables consist of analytic outputs that translate operational data into decision-ready information. WSP's Benefit-Cost Analysis, built in Excel for transparency and adaptability, analyzes inputs ranging from average land values and operator walk times, to retrofit costs and charging-equipment prices, then computes monetized annual savings for each use case. TTI's Job Impact Calculator works at the job level, comparing current tasks, daily hours, and KSAs with projected post-automation requirements to estimate labor-hour shifts, job gains or losses, and new training needs. Both models produce CSV tables that can be generalized to agencies of similar size or operating context.

Additional streams look ahead to capabilities expected in the next project phase. Phase Two envisions an automated fleet dispatch system which will issue real-time missions based on vehicle position, state of charge, preventive-maintenance status, and scheduled service needs. Although only high-level requirements are captured in the current DMP, the team commits to expanding this section should there be subsequent phases, supplying a more granular map of data exchanges and control messages.

ACCESS, STORAGE, AND REDISTRIBUTION

All YARD datasets will be openly accessible via CapMetro's MetroLabs Open Data Portal under a CC BY 4.0 license, enabling attribution, commercial use, derivative works, and adaptations with the requirement of retaining appropriate credit to the FTA and project partners. During active development, data stays on secured BTS networks and drives backed up nightly and are later archived in the National Transportation Library's (NTL) ROSA-P. Persistent Digital Object Identifiers (DOIs) minted by NTL staff will link each dataset to its repository landing page, ensuring discoverability and perpetual preservation. ROSA-P's compliance with the Department of Transportation's (DOT) Public Access Plan, daily backups across DOT, Center for Disease Control (CDC) and Amazon Web Services (AWS) servers, guarantees both the resilience of YARD Program data.

CONCEPT OF OPERATIONS

In 2024, prior to Demonstration Two, WSP wrote a 39-page Concept of Operations document which detailed the current systems in use at CapMetro North Ops, as well as the proposed automation system that would be deployed in the pilot program later that year. The goal of CapMetro's Yard Automation Research and Deployment (YARD) Concept of Operations was to:

- Give an overview of the objectives, needs, and constraints of the proposed system.
- Facilitate stakeholder agreement on system operation, responsibilities, the environment in which the system will operate, and the processes required to validate the system.
- Analyze and mitigate challenges and limitations that are discovered or proposed.

SAFETY PLAN

This document served as a plan to highlight the protocols and steps taken during the CapMetro ADS YARD project to address the risks associated with an AV demonstration and ensure the safety of all participants, including the CapMetro employees working in and around the North Ops bus depot.

This document was intended to:

- Ensure alignment between CapMetro YARD stakeholders, and Perrone Robotics Inc. (PRI) to meet the safety & security guidance set forth in this document throughout the testing phase.
- Create a foundation for CapMetro and the broader transit community to safely test and deploy automated battery electric buses in the future when ADS and ADAS technology becomes more readily available.
- Inform the CapMetro Test Plan of what safety protocols must be included within Acceptance Testing.

CAPACITY ANALYSIS

One of the key hypotheses that this project wanted to explore was the effect of automation on the capacity of a given bus depot, in this case CapMetro North Ops bus depot. Automated vehicle operations could allow for more efficient charge management, charger layout, and parking layout due to a reversal of common bus yard wisdom—instead of moving electrons we would move the buses. WSP's original hypothesis estimated:

- Increased space efficiency would increase bus yard capacity by up to 35%
- Decreased need for chargers would reduce the number of overhead pantograph chargers by up to 25%
- No changes to energy needs or cost

ChargeSim was brought on as a subcontractor to complete the analysis and quantify the exact effect that automation could have on the North Ops Depot. The main questions ChargeSim needed to answer were:

- How many chargers were required for automated versus traditional operation?
- How can the layout be optimized for automation?
- How much space is saved?
- Are there any changes in grid requirements?

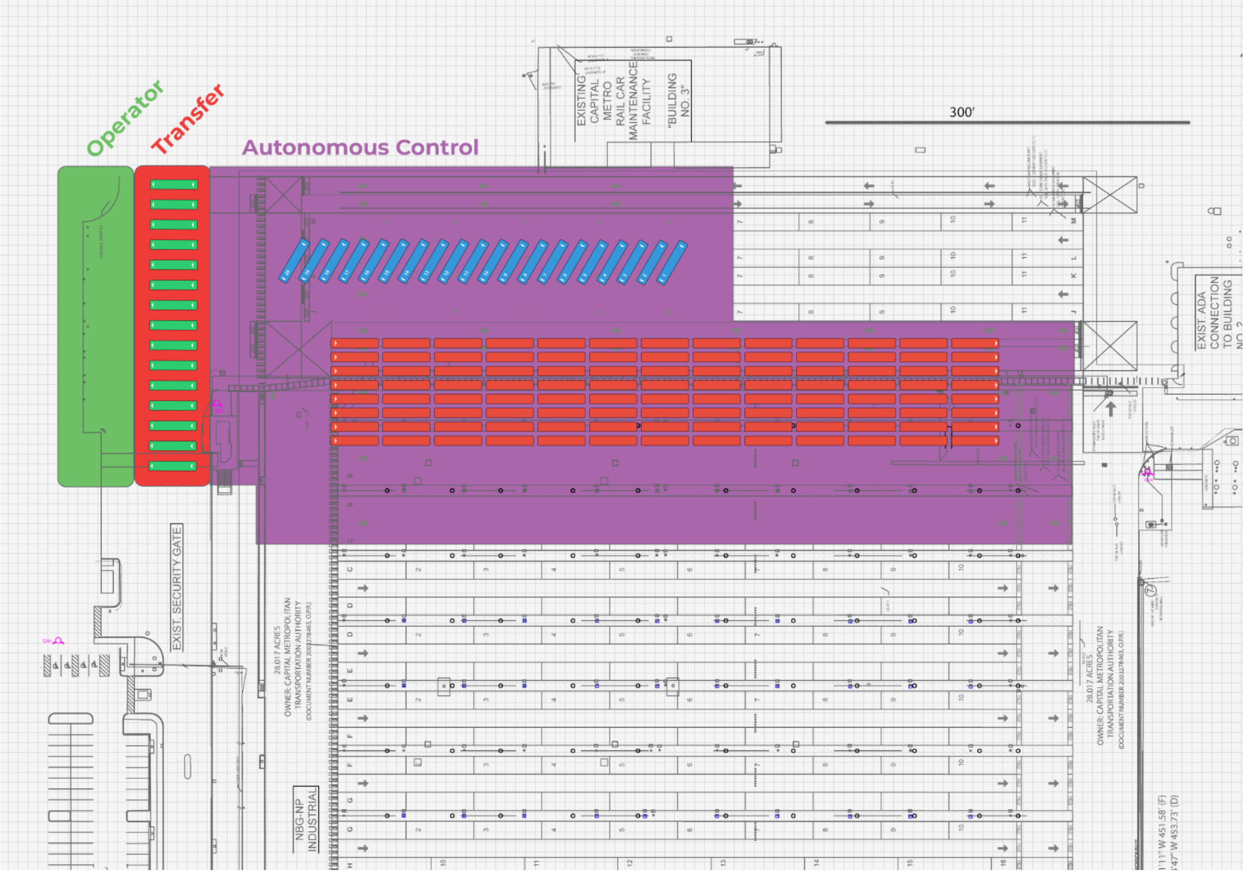
CapMetro provided ChargeSim with Computer Aided Design (CAD) plans—Figure 3-1—which show the current parking arrangement and spacing as seen in Figure 3-1. CapMetro's North Ops is a large bus depot with a parking area footprint of 470,000 square feet. There are 20 parking lanes and 12 one-way travel lanes. Each bus is allotted to a 56-foot parking pitch. This allows each bus to pull in or out of their space and into a travel lane independently without needing any other vehicles to move.

Figure 3-1: Current Layout of North Ops at Full Capacity

At full capacity, North Ops yard can hold 200 buses utilizing the layout above. If all 200 buses were battery-electric, CapMetro's North Ops fleet would require 200 pantograph dispensers and 70, 180kW chargers at a 3:1 dispenser to charger ratio, to charge all the buses overnight. At an industry average unit cost of $190,000 for a 180kW charger and three dispensers, the charging infrastructure would amount to $13.3 million.

The layout in Figure 3-2 is one of many potential designs for a parking layout which takes advantage of the benefits of automated vehicles. The purple area is the automation zone, the red area is the transfer zone, and the green zone is for human operators only. Compared to the traditional layout above, this design only utilizes 222,000 square feet, a 53% reduction in space used.

Figure 3-2: Potential Layout for Automated Yard



In this example of a potential scenario, the vehicles in the purple zone will be facing to the right in the diagram, travel in a counterclockwise pattern, and then park in the transfer zone facing to the left of the diagram and await human operators for pull-out or maintenance. As the vehicles will park and navigate autonomously in the purple zone, no walkways or pull-out areas for humans will be required, and consequently the vehicles can be parked much more tightly together. It is important to note for transit agencies in general, that such design optimization should occur prior to major infrastructure updates such as installing charging cabinets and associated electrical equipment for the capacity benefits to be realized. The spaces here would utilize spacing of 6-foot nose-to-tail and 3-foot side to side between each bus[1].

Compared to a traditional layout, this automated design only utilizes 222,000 square feet, a 53% reduction in space used.

[1] Nose to tail and side to side spacing indicate the distance between two parked buses, measured both side body panel to side body panel, or rear bumper of bus 1 to front bumper of bus 2.

If someone does need to access a vehicle in this zone, there will still be plenty of space for them to walk between buses. However, it is important to note that while there are potential capacity savings with automating a battery electric bus (BEB) fleet, the agency will need to thoroughly prepare for a potential thermal event[2] to occur. Parking BEBs closer together increases the risk of a fire spreading more quickly. An automated solution to a thermal event occurring is a requirement the project team intends to test during subsequent phases. The fleet of three automated BEBs will receive a message from the automated fleet dispatch software to remote start and drive to a safe location after the detection of a thermal event related fault is detected and communicated to them.

The angled spots at the top of Figure 3-2 are reserved for charging vehicles only. In this example the automated charging will be performed by overhead pantograph dispenser. These spots are designed to be drive-in/drive-out. The vehicles will enter the spaces by utilizing the counterclockwise pattern described earlier, then once charged can drive straight through the parking spot and go to the transfer zone or return to the parking area in the automation zone. This eliminates the need for vehicles to reverse, which would necessitate more sensors to perform and incur greater risk. Additionally, as the vehicles can move in and out of the charging areas autonomously, this configuration would only require 14 pantograph dispensers and 14 360kW chargers. At a unit cost of $500,000 for a 360kW charger and one pantograph dispenser, the charging infrastructure would cost $7 million. This represents a $6.6 million decrease in charging infrastructure costs. The increase in power output over the nominal case is to decrease charging time to allow for more vehicles to utilize a single pantograph over a given period. ChargeSim's simulations show that for the buses to perform the charging and parking required, the automated fleet would average 20 movements per hour in an overnight period from 12am to 6am. These movements would include both travel to and from the charger, as well as shifting forward in the parking area to allow returning buses to park in their assigned lane.

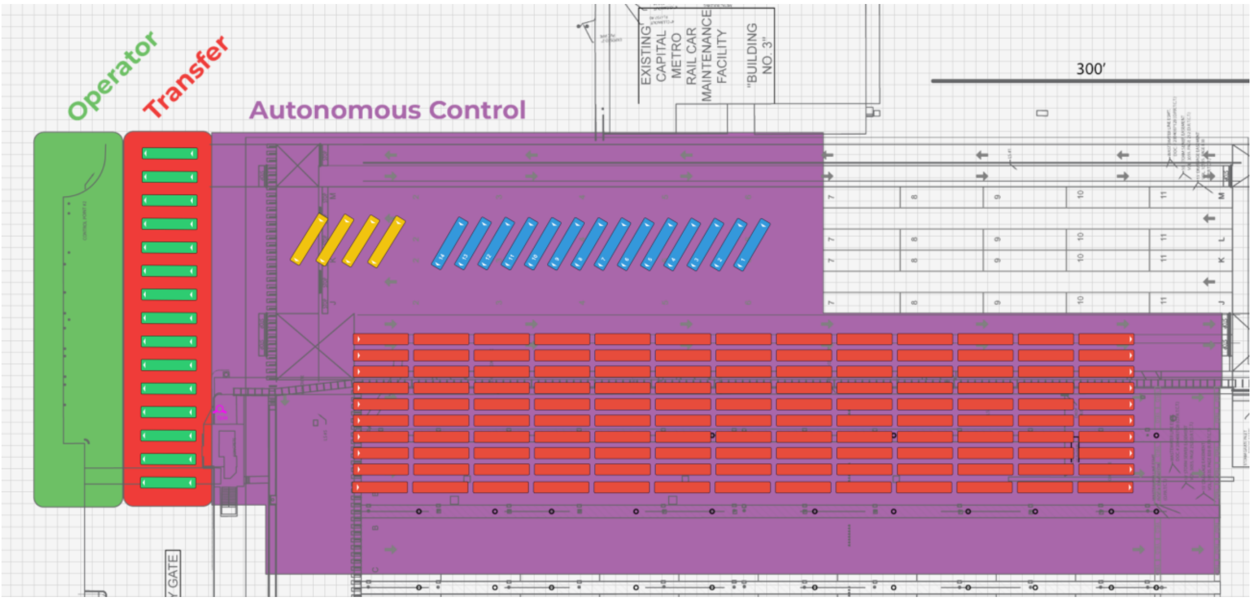
Being able to use fewer, higher wattage 360kW chargers and using automation to automatically switch which bus is charging throughout the night, amounts to a savings of $6.6 million in charging infrastructure costs.

Figure 3-3 below is very similar to Figure 3-2's design, with a slight change to the charging layout to allow for dedicated interior cleaning spaces shown in yellow. This design has dedicated cleaning spaces to allow for an automated recall mission to bring the bus to a cleaning station where tools and supplies are available for personnel. Additionally, having the cleaning station close to the transfer zone means that staff won't have to venture far into the autonomous zone or walk in-between vehicles. This would require additional automated recall missions to be programmed, in addition to those mentioned with respect to Figure 3-2, to be

[2] A thermal event is the detection of a battery related issue which can result in the combustion of one of the BEBs batteries.

programmed. While this may add complexity to the automated workflows, it would not affect bus capacity or charger quantity.

Figure 3-3: Potential Layout for Automated Yard with Cleaning Area



For a fleet of 200 BEBs, the automated configuration would only require 14 pantograph dispensers and 14 360kW chargers versus 200 dispensers and 70 180kW chargers— an 80% reduction in the number chargers needed and 93% reduction in the number of dispensers required.

BENEFIT-COST ANALYSIS (BCA)

The BCA approach followed the methodology laid out in the FTA's Strategic Transit Automation Research (STAR) plan 1.0[3] for identifying use cases of transit automation resulting in benefits. WSP extended the recommendations with specific inputs and assumptions relevant for operations in CapMetro's North Ops. Yard. The studied use cases to quantify benefits in the BCA include:

- **Parking and Recall, Yard service movement**: Operator and Yard hostler time savings arising from automated pull-in/pull out maneuvering (aided by ADS technologies) were computed using North Ops' depot layout and validated with distance/walking time data collected on-site
- **Automated Charging**: Fewer overhead dispensers are anticipated through shared fleet charging. The current BCA used information from a recent study conducted by ChargeSim for anticipated reduction in chargers.

[3] https://www.transit.dot.gov/sites/fta.dot.gov/files/docs/research-innovation/114661/strategic-transit-automation-research-report-no-0116_0.pdf

- **Automated Precision Parking:** An increase in yard capacity resulting from capabilities offered by ADS technologies can produce quantified depot cost savings using average real-estate costs per sq ft for CapMetro (that can also be accommodated to support potential fleet growth). The current BCA used information from a recent study conducted by ChargeSim for anticipated increase in yard capacity.
- **Safety:** Reduction in in-yard (ADS) and in-revenue (ADAS) incidents were quantified using baseline crash statistics data from CapMetro and National Transit Database (NTD) respectively and anticipated reduction in crash rates enabled by these technologies as established in the literature and FTA methodology. The reduction in crash risks also leads to potential reduction in insurance-related liability and casualty savings (insurance payments)
- **Electricity Savings:** Lower electricity cost is anticipated by optimizing charging schedules to take advantage of off-peak rates and avoid demand spikes. The current BCA used information from a recent study conducted by ChargeSim for anticipated reduction in electricity usage.

The analysis included both the capital and O&M costs related to the following major expenses:

- Retrofitting CapMetro's current total BEB fleets (104 buses) with ADS technologies (inputs from PRI)
- Phased integration of the BEBs with the automated fleet dispatch system over a period of 10 years (inputs from Clever Devices) as shown in Table 3-1.

Table 3-1: BEB Phasing Schedule

Year	Number of Buses	Cumulative Number of Buses
2025	1	1
2026	2	3
2029	10	13
2030	10	23
2031	12	35
2032	12	47
2033	13	60
2034	14	74
2035	15	89
2036	15	104

BCA FINDINGS

As mentioned above in Table 3-1, the ADS retrofitting of CapMetro's current fleet of 104 battery-electric buses would require a phased rollout of 10 years. The ADS retrofit and 10-year phased integration detailed above is expected to cost $69.3 million in undiscounted 2025 dollars through 2036. At a 3.1 percent real discount rate, these costs are $50.7 million. The fleet automation program would be expected to generate $164.8 million in discounted benefits using a 3.1 percent discount rate. The fleet automation program generates these benefits mainly by reducing fatalities and injuries from vehicles and saving operational time. Other benefits include depot cost savings, electricity savings as well as saving in vehicle operation costs, liability and casualty costs, and wireless charger costs. This leads to an overall project Net Present Value of $114.1 million and a Benefit Cost Ratio (BCR) of 3.25. The overall project benefit matrix can be seen in Table 3-2.

Table 3-2: Summary of Bus Automation Benefits and Costs

BCA Metrics	Value ($M)[2]	Description
Total Benefits	**$164.8**	
Safety Benefits (In-Yard)	$4.3[4]	Automation technology includes automatic emergency braking and object detection, thereby reducing vehicle collisions.
Safety Benefits (In-Revenue)	$132.3	Automation technology includes automatic emergency braking and object detection, thereby reducing vehicle collisions.
Operational Time Savings	$19.3	The bus will autonomously navigate from its parked location to a designated transfer zone, which will result in a significant reduction in the operator's operational time and therefore allow to repurpose labor hours elsewhere or keep the savings and reinvest.
Liability and Casualty Cost Savings	$3.7	The reduced in-yard and in-revenue crashes due to automation will also reduce the insurance-related liability and casualty cost.
Depot Cost Savings	$2.2	Increased allowance for efficient use of bus yard space, including tighter parking in lanes, will result in depot cost savings, which are calculated based on average real-estate costs per bus parking space
Charging infrastructure Cost Savings	$2.6	BEBs equipped with automated bus technology would streamline the charging process, therefore reducing the number of wireless chargers needed.
Electricity Cost Savings	$0.4	BEBs equipped with automated bus technology would lower electricity costs primarily through smart charging management and optimized energy use
Total Costs	**$50.7**	Total costs included capital costs for retrofitted buses as well as BEBs Operation and Maintenance (O&M) cost
Benefit-Cost Ratio	**3.25**	Overall metric to assess worthiness, single ratio comparing benefits and costs over project timeline.
Net Present Value (NPV)	**$114.1**	Difference between the present value of benefits and costs.

[4] The range of North Ops historical data used for this analysis did not include any severe or fatal injuries in yard, thereby reducing the benefits in comparison to In-Revenue incidents. Such injuries can represent dramatic costs for the agency.

Concerning the associated In-Yard Safety Benefits for bus yard automation, more work is needed in this area to determine vehicle, infrastructure, and personnel incidents that could be avoided with ADAS and ADS technologies. Additionally, the ability to determine the full cost of the incident, which includes downtime of vehicle, worker's comp, and potential repairs will further refine the safety benefits associated with this technology. Finally, fleet incidents occurring in the yard are sometimes not logged appropriately as this would incur a strike against the operators record whereas if the incident occurs in revenue service, the operator is less likely to receive a strike against their record. This assumption does not imply that these experiences are occurring at CapMetro, but this scenario has been observed at other agencies across the U.S.

4. SOFTWARE ARCHITECTURE - CLEVER DEVICES

SCOPE

Clever Devices undertook a comprehensive approach to design and document a robust and tailored solution that incorporates automated fleet technology, real-time yard management software, and charge management systems. This design process identified areas where new development was needed, and how the new implementation will co-exist with existing features, and other third-party systems. A foundational step in this phase was gathering detailed use cases from CapMetro to craft precise user requirements. This process involved in-depth consultations, through the form of workshops, and analysis to ensure that the solution's design would effectively address the various use cases of the YARD project.

WORKSHOPS

As part of the Phase One deliverables, Clever Devices hosted two workshops with CapMetro to collaboratively advance the YARD project. These workshops served several key purposes, the most important of which was providing a platform for updating CapMetro on the latest design, allowing for real-time feedback and adjustments. Additionally, Clever Devices facilitated a thorough review of potential concerns and formulated actionable plans to address these issues, ensuring a proactive approach to problem-solving. Furthermore, the workshops were instrumental in helping Clever Devices gain a deeper understanding of CapMetro's specific operational use cases and third-party integrations, which was crucial for tailoring the final report to meet their needs effectively. To prepare for Workshops one and two, periodic meetings were held with various participants, and experts of potentially affected systems to analyze and determine whether new development is required. While Clever Devices aimed to design a general, open solution, the workshops provided insight into the specifics of CapMetro's infrastructure environment in preparation for Phase Two of the project. This collaborative process aimed to ensure that the autonomous yard will integrate seamlessly with CapMetro's operational requirements while addressing any challenges proactively.

KEY ACTIVITIES AND OUTCOMES

Clever Devices key activities and outcomes from Phase One of the Yard Automation Research and Deployment project can be summarized as the following:

- Defined user requirements and use case scenarios to meet the objectives of the YARD Project.
- Identified potential areas of concern and provided mitigation plans.
- Reviewed day-to-day operational behaviors at CapMetro to incorporate into the final design.
- Confirmed the current layout (for Phase One) and the future changes, installations, and construction of the North Ops Yard (for Phase Two, and beyond).
- Educated CapMetro and project participants on the roles that SmartYard and the EVMS Microservice will play in the design.
    - SmartYard, the Real-Time Yard Management System, will be handling the integration with Perrone Robotics so that all autonomous vehicles and their locations can be visualized in a web-based client.
    - SmartYard will also dictate where the vehicle will need to navigate according to a configured Parking Plan.
    - Whereas, the EVMS Microservice will act as the Charge Management System and integrate with the electric vehicle battery chargers, and the vehicles to acquire real-time state of charge (SoC) status.
- Created a draft map of the North Ops yard to illustrate the ideal autonomous bus navigation paths.
- Specified all third-party systems within CapMetro's environment to jumpstart integration and design discussions. This will help identify any additional scope that is required in preparation for the Phase Two project.
- Provided updates to the system architecture, schematics, messaging interfaces, and overall feature additions to the SmartYard and EVMS Microservice products in preparation for Phase Two.

For more insight into the Clever Devices design, engineering, and documentation of the yard management system, please refer to the document *Yard Automation Research and Deployment: Phase One- Clever Devices.*

5. WORKFORCE ANALYSIS - TTI

SCOPE

The workforce analysis included an assessment of current roles and responsibilities at CapMetro North Ops bus depot, focused on positions directly or indirectly impacted by automation technology. Additionally, analysis included recommendations for changes to current positions and the development of potential new roles based on the planned maneuvers of the automated bus yard. Phase Two recommendations that highlight how CapMetro may develop a training curriculum to support changed positions or new fleet automation roles are also included.

WORKSHOPS

The purpose of this task was to work with CapMetro staff and determine (1) how bus yard procedures would change under an automated yard scenario and (2) how those procedural changes may impact the workforce in terms of time spent on tasks as well as the knowledge, skills, and abilities (KSAs) needed for each position. Over the course of the project, TTI held two workshops.

The first workshop served as a kick-off workshop for the workforce analysis for the project. The workshop was for middle-management, supervisor, and front-line employees involved in maneuvering buses in the yard. The workshop was 1.5 hours long and had the following agenda:

- Overview of the YARD project, including the general workforce philosophy.
- Overview of the workforce analysis, including tasks and asks
- Discussion of current yard operations, roles, and responsibilities
- Discussion of next steps

The second workshop TTI facilitated for the project was attended by selected front-line and middle-management staff from positions directly and indirectly impacted by yard automation. Workshop attendees included, but were not limited to, one or two representatives from the following positions / categories:

- Bus operators
- Yard management
- Bus maintenance
- Cleaners / fuelers / washers

TTI then used a job impact calculator[5] to quantify the potential changes in labor hours needed from all the directly impacted front-line positions that may be affected most significantly by automating the bus yard. Results from the job impact calculator were vetted with the project team and CapMetro staff.

SITE VISITS

In addition to the two workshops, TTI completed two site visits to better understand daily operations at the North Ops yard. TTI was authorized to be on-site at the North Ops bus yard for anytime over a period of one week to observe bus movements and staff interactions with buses, have brief interactions with staff on duty (e.g., service island employees and operators), and take photos. The site visits included:

- First Visit
  - Observation of the AM pull-out, from 4 AM to 8 AM

[5] The job impact calculator will be provided as part of the Data Management Plan.

- Observation of the mid-day pull-in period, from 10 AM – 1 PM

- Second Visit
  - Observation of the PM pull out from 3 PM – 6 PM
  - Observation of the PM pull in and late-night yard operations, from 8 PM – 11 PM

POSITION INTERVIEWS

Position interviews helped TTI ensure they fully understood the duties of affected positions. Though TTI anticipated needing to hold only five interviews, they conducted eight. Table 5-1 shows the staff that were interviewed:

Table 5-1: Interviewees Selected for Position Interviews By TTI

Name	Organization	Title
Kory Overby	CapMetro	Vehicle Maintenance Instructor
Philip Pumphrey	Keolis	Assistant General Manager (North Ops)
Juan Mendez	CapMetro	Superintendent, Vehicle Maintenance (North Ops)
Marcus Wright	CapMetro	Superintendent, Training
Olivia Jones	CapMetro	Director, Operations Control Center and Training
Rafael Villarreal	CapMetro	Senior Director, Transportation
Gareth Graham	CapMetro	Superintendent, Parts, and Inventory
Eric Knutzen	Keolis	Maintenance Manager

During these interviews, TTI:

- Presented the draft job profile to the attendee(s).
- Sought feedback on the draft job profile.
- Collected information on potential re-skilling / up-skilling ideas under a fully automated yard scenario.

KEY OUTCOMES

This research helped provide insights into how current yard operations would likely change under an automated yard scenario and how the workforce would be potentially impacted. This section highlights the key takeaways from all aspects of work completed including workshops, site visits, position interviews, job impact calculator analysis, and conclusions drawn from the final workforce analysis.

- **Labor hour impacts are varied.** The net percentage change in labor hours across the directly impacted front-line positions varied significantly—from no change for bus operators to a 100 percent reduction for the puller / parker role of service island attendants.

- **Bus operator impacts are minimal.** Apart from having to understand the new processes for yard operations, the direct impacts of yard automation on bus operators are minimal. The time savings from not having to walk to or from buses in the yard would likely not be significant enough to generate actual time or cost savings for transit agencies, especially if the time savings are simply re-invested back into revenue service.

- **Maintenance impacts are mainly in the electronics shop.** Because of the existing expertise in the electronics shop, it is reasonable that the electronics shop would be the main department for maintaining the automation-enabling systems on equipped buses. This will likely require:
    - Additional training for Mechanics / Techs in the Electronics Shop.
    - Hiring additional staff when deployment is scaled up.
- **Labor related to BEB charging significantly reduced.** Currently, several staff are involved in monitoring BEB charging and cycling buses through charging. With buses being able to position themselves autonomously and initiate charging at an overhead dispenser, the labor hours spent on BEB monitoring and cycling would be reduced.
- **New positions would be needed.** Under an automated yard scenario, there is a significant reduction in the number of manual bus movements in the yard due to the reduction in the labor hours spent moving buses—especially for the service island attendant puller / parker role. However, a need remains for qualified staff in the yard dedicated to overseeing yard operations and being available to move buses manually when needed. CapMetro and the research team conceived two new positions: the *Yard Hostler* and its direct supervisor, the *Yard Supervisor*.
- **Reduced workload on service writers:** Given the yard management system (YMS) knows the location of all buses in the yard, service writers would no longer have to walk the yard to produce the yard map or - assign buses to blocks every day. Other current roles for service writers are also reduced, for example, service writers would not be responsible for monitoring the charging status of BEBs.

Table 5-2 below describes each position, the impact an automated bus depot may have on that position's responsibilities, and the net change in labor hours needed expressed as a percentage. Many of the positions do have decreased responsibilities—and therefore a negative net change in labor hours needed—however there are also net increases and entirely new positions being created as well. This information was generated by TTI's job impact calculator which—using use cases, level of effort, effective daily hours, and more—was able to generate the percentages below.

Table 5-2: Potential Position Changes- Task and Labor Hours

Position	Summary of Task Changes	Net Change in Labor Hours
Bus Operator	Reduce yard walking; time reinvested in other tasks	0%
Bus Mechanic: Yard Operations Support	Increase time spent on maintenance and troubleshooting issues in the yard	9%
Bus Mechanic: Electronics Shop	Increase inspection and maintenance	10%
Service Writer: Day	Reduce yard walking / bus assignment	-16%
Service Writer: Night	Reduce yard walking / bus assignment (Net decrease more than day shift, because AM bus assignment task eliminated)	-75%
Service Island Attendant: Probe Shack	No change	0%
Service Island Attendant: Fuels / Oil	Less time checking and replenishing fuel & oil	-44%
Service Island Attendant: Sweeping / Mopping	No change	0%
Service Island Attendant: Windows / Dashes	No change	0%
Service Island Attendant: Puller / Parker	No need to pull / park buses	-100%
Yard Supervisor (New)	New position to help supervise use of YMS, manage pull-out queue, and conduct post-revenue service inspection to release buses for yard automation (able to be engaged in automated mode)	NEW
Yard Hostler (New)	New position to help manage pull-out queue, assist with pull-out tasks in the yard, assist with inspecting buses post-revenue service, and move buses in the yard when they are not released for yard automation	NEW

Note: The percentages shown in the table are the estimated net change in labor hours for the position caused by the combination of the yard management system, yard automation, and fleet electrification. Many assumptions underly these estimates, and these values should not be seen as final or definitive.

For more insight into Texas A&M Transportation Institute's observations, calculations, and insights into the workforce analysis please refer to the document *Yard Automation Research and Deployment: Phase One- Texas A&M Transportation Institute*.

6. BUS AUTOMATION- PRI

DEMONSTRATION ONE

The first automated vehicle demonstration at CapMetro's North Operations Yard utilized an automated Level 4 cutaway electric shuttle. This demonstration had two key goals. The first and main goal was to showcase the capabilities of Level 4 automation on the subject vehicle within the North Ops bus yard to CapMetro personnel. The second goal was to collect operational data to better prepare for the second demonstration.

To achieve these goals, the project partners planned a route in the bus yard with several maneuvers which would pique the interest of attendees and offer a first look at the accuracy and precision of Perrone's automation kit and overall feasibility of an automated bus yard. The maneuvers executed were path following, object detection and avoidance, and precision parking[6].

The route of the vehicle started on the north side of the lot, where buses would normally enter after service and extended counterclockwise around the perimeter of the bus yard until arriving back at their starting location. The project team called this location the demonstration staging area. This is where the demo attendees boarded the bus. The vehicle used for the first demonstration was a Greenpower cutaway shuttle supplied by PRI. The Greenpower shuttle was outfitted with PRI's TONY AV Kit and MAX software. This implementation of hardware and software included:

- 2 front-corner mounted lidar
- 1 front mounted radar
- 1 rear mounted radar
- Navigation modem and dual GPS antenna on the roof
- Internal inertial measurement unit (IMU)
- AV compute system
- Driver tablet running PRI MAX software.

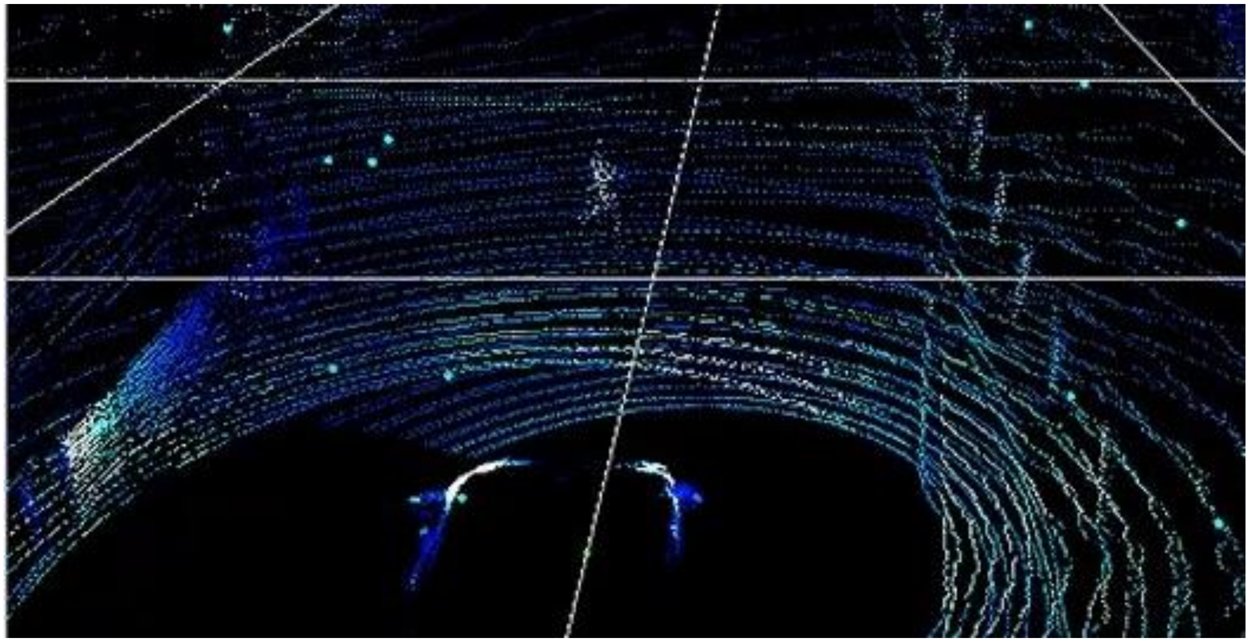
Due to the geometry of the shuttle compared to the 40' battery electric bus used for demonstration two, the sensors were mounted differently. As seen in Figure 6-1 below, the two lidar are mounted on opposing front quarter panels to give an optimal field of view, and there is also a radar embedded in the front bumper.

[6] Automated Driving Concepts and Term definitions can be found in the Glossary.

Figure 6-1: Perrone Robotics Automated Cutaway Shuttle

The demonstration went quite smoothly with all maneuvers being performed confidently and safely. Figure 6-2 showcases some of the live pedestrian object detection and avoidance maneuvers that were performed during the demonstration. Also, during the demonstration, PRI was able to answer attendee questions about the operation of the vehicle, regulations, and next steps in the project.

Figure 6-2: A person walking in front of the cutaway vehicle during the demo as detected by lidar and radar.



RETROFIT

Prior to the second demonstration, the BEB retrofit activities took place at PRI's headquarters in Charlottesville, Virginia where the hardware and software installation, configuration, and initial testing occurred. Once the retrofit was completed, project stakeholders, including CapMetro and members of the FTA, traveled to Virginia to observe the retrofitted bus capabilities prior to the automated BEB being shipped to Austin, Texas.

NEW FLYER XCELSIOR BATTERY ELECTRIC BUS

The bus platform, Figure 6-3, has the following specifications per the manufacturer, New Flyer:

- Length – 41' (bumper to bumper)
- Width – 8.5'
- Height – 11' 1"
- Weight – 32,700lb
- Wheelbase 23.6'
- Battery – 466 kWh

The sensing capabilities required for automated bus operation will be confined to the vehicle itself—apart from GPS and cellular real-time kinematic (RTK) and no sensing infrastructure support was required to be installed at North Ops for Phase One.

Figure 6-3: New Flyer Xcelsior Charge Battery Electric Bus

AUTOMATED DRIVING SYSTEM MODULES

PRI's TONY automation kit consists of sensors, actuator, microcontrollers, and compute systems, which together, are capable of navigating vehicles at highway speeds. This far exceeds the requirement for the in-yard use case but demonstrates the system's robust capabilities. The software inside of the TONY system, called MAX, is a full-stack automated software platform which is vehicle and sensor agnostic and is extremely energy-efficient, which provides a distinct advantage for BEBs.

The following modules installed by PRI into the New Flyer Xcelsior battery-electric bus are what enable the vehicle to perform the automated maneuvers and drive autonomously without operator oversight:

- **Power Distribution**- This module is designed to connect to the 12V system of the vehicle and distribute power to all other modules and sensors (minus the steering module).
- **General Purpose Input/Output**- This module houses hardware for signal input and output.
- **Serial**- This module contains hardware for communicating to actuators and sensors.
- **Compute System-** The brain of the vehicle capable of sending signals to the vehicle control systems to physically move the vehicle in the operational design domain (ODD) for which it has been configured. Computationally reliant on powerful CPUs (computer processing unit), GPUs (graphics processing unit), or custom SoCs (system on a chip) which are made precisely to be able to manage the millions of calculations and data throughput needed to drive a vehicle and react to sensor inputs in real time. The compute module runs PRI MAX software and controls all aspects of automated operation.
- **Logging-** This module collects and stores information from MAX processes and sensor outputs.
- **Watchdog and BISC-** PRI subsystem which provides continuous oversight of the system to verify proper functionality.
- **Communications-** The communications module allows for 5G/4G internet communications for the TONY Kit which has restricted access and is used only for localization in addition to the navigation module.
- **User Interface-** A tablet is mounted inside the vehicle to set up automated missions and display information useful to the safety operator of the bus and automated system.
- **Navigation-** This module is used for acquiring the positioning of the vehicle and consists of two antennas mounted to the roof and a receiver unit inside the vehicle all ideally mounted on the centerline of the vehicle.

DRIVE BY WIRE MODULES

The following components are to be fitted to the BEB to enable the automated system to perform the actions of a driver:

- **Steering Module-** A rotary stepper motor is attached to the steering wheel column using a collar, and a belt is used to transmit steering torque.

- **Brake Module-** A linear actuator is used to depress the brake pedal enabling control of the brake system.
- **Throttle Module-** As the throttle position is transmitted to the electric drive using a controller area network signal (CAN), a CAN wiretap was used to transmit throttle signal to the vehicle control system.
- **Shift Module-** Shifting was performed by emulating shift signals of the OEM shifter using the TONY Kit through a CAN wiretap.

SENSORS

Radar
Automotive radars usually use a frequency in the 76-81 GHz range. As a standalone sensor, radar is quite capable of tracking moving objects, has an exceptionally long range, is inexpensive, works in both low light and adverse weather conditions, but it can suffer from a lack of clarity. This can sometimes result in perceiving individual objects clustered together as a singular mass. In this application it will be used for long range object detection and tracking.

Lidar
Lidar on the other hand is expensive, its data quality suffers during adverse weather such as rain or snow, and it has less range. But when the conditions are right, it does have a superior image quality, which is why it is used for high resolution 3D scans. In this application it will be used for short range detection and tracking with high fidelity.

Camera
Used mostly for detection applications which rely on color or text, like classifying signs or traffic light colors. Cameras can be used in conjunction with radar and lidar via sensor fusion to help classify objects. Stereo cameras can be used to derive distance, and therefore be used in place of radar, but fall short in terms of latency, low light performance, and adverse weather performance.

IMU
An inertial measurement unit (IMU) is an electronic device that measures and reports a body’s specific force, angular rate, and sometimes orientation. In the context of autonomy, an IMU provides valuable feedback to the AV computer about current acceleration and deceleration values.

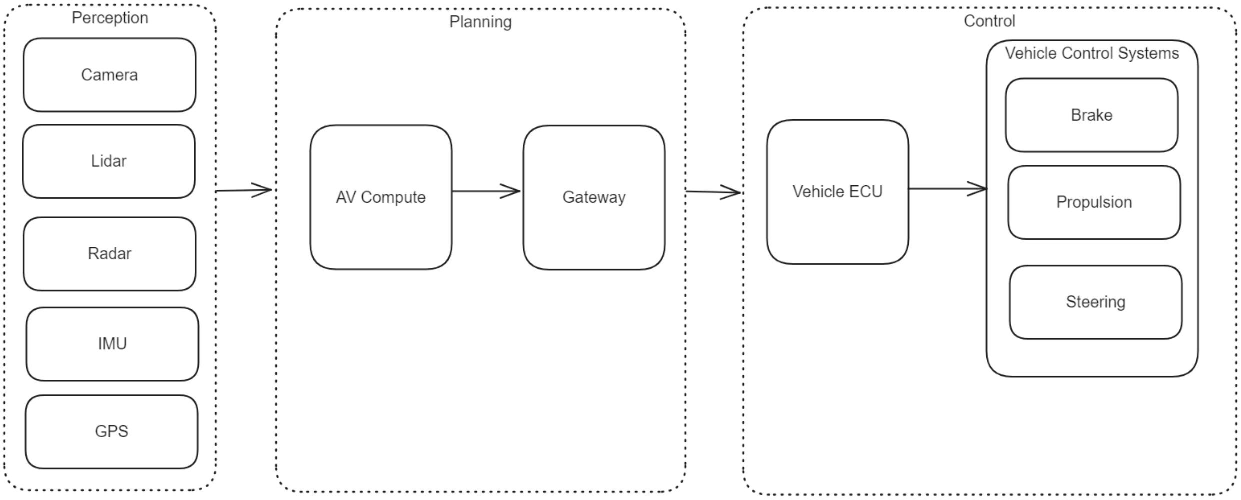
GPS
The Global Positioning System (GPS) module is an essential part of the localization process. Modern GPS modules can accurately locate the subject with centimeters of precision. In the case of automated vehicles, this information tells the AV computer where it is in the world. Combined with ground truth, known road features detected by sensors, and mapping data, the AV computer can precisely localize itself.

SYSTEM DIAGRAMS

Integrated System

An integrated system is one that uses the existing vehicle controls systems to carry out the actions the AV compute system requests. In this type of system, a Controller Area Network (CAN) gateway between the AV compute system and Vehicle control ECU is required to translate the AV messages onto the CAN bus of the vehicle. From there the AV compute system can command each control system to respond to its inputs. This type of integration requires a drive-by-wire vehicle platform and integration into the vehicle CAN network. This is more difficult to initially implement but it is far easier to scale up when a full deployment is necessary due to the minimal external system as shown in Figure 6-4.

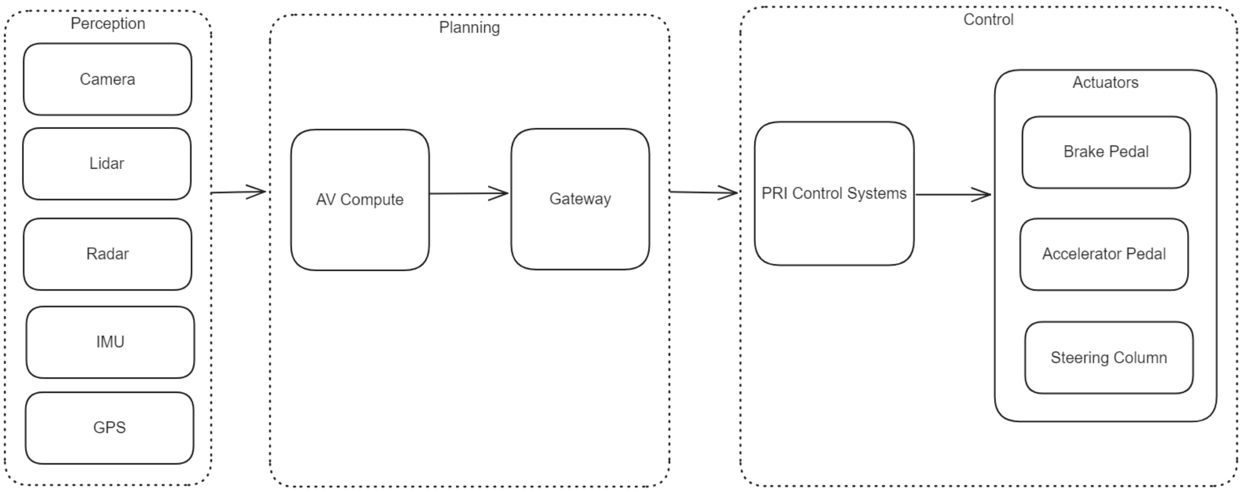
Figure 6-4: High-Level Integrated System Diagram



"Over the Top" System

An "over the top" system is one that uses the external actuators to physically move the control interfaces to carry out the actions the AV compute requests. In this type of system, a CAN gateway is still needed between the AV compute and control interfaces, but instead of sending messages to the vehicle platform, it is sending messages to the control systems that will be physically manipulating the brake pedal, acceleration pedal, and steering column. This type of system is easier to implement but is harder to scale, and therefore suitable for proof of concepts. Figure 6-5 below illustrates this concept.

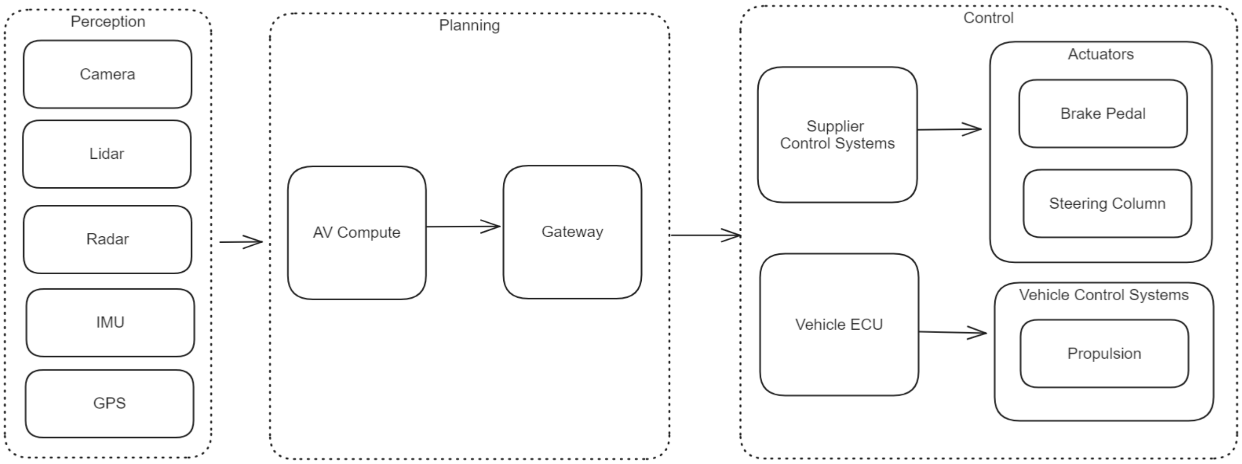
Figure 6-5: High-Level Over-The-Top System Diagram



Combination System

PRI implemented a combination of both systems as seen in Figure 6-6 below. The braking and steering systems were handled by PRI's control system physically actuating the steering column and brake pedal, while the throttle was manipulated on a signal level. The throttle position sensor of the New Flyer BEB has a 6-pin connector connecting it to OEM vehicle systems. A male and female version of this connector were wired to add a throttle tap access point which can be used to forward new signals onto the throttle position sensor CAN bus. The tap is connected to the TONY system which sends the proper inputs to the sensor to accelerate the vehicle.

Figure 6-6: High-Level Combination System Diagram



PHYSICAL SENSOR LAYOUT

After various simulations and tests, PRI decided on the final sensor suite, Figure 6-7, which included only radar, lidar, and GPS. This suite of sensors was chosen specifically for this automation project and the ODD of CapMetro North Ops. The sensors allowed the bus to complete all prescribed use cases and automated features.

Figure 6-7: Planned Sensor Layout on 8002

Ultimately the front-facing radar and LIDAR were not used due to interference from the existing bike rack present on bus 8002. In fact, the final sensors, seen below in Figure 6-8, with their almost 180-degree vision, needed exclusion zones imposed to digitally ignore the bike rack from being always seen as an obstruction.

Figure 6-8: LIDAR and Radar (inside enclosure) mounted to the front bumper of CapMetro bus 8002

DEMONSTRATION TWO

Demonstration Two had multiple stages. The first stage required that a safety operator always be present in the driver's seat of the automated bus in case an intervention is required. Once the acceptance criteria were met, the project moved to the second stage, where the safety driver was removed from the driver's seat (though they will remain onboard with access to an emergency stop button). Both stages underwent similar testing.

The full scope of testing encompassed the four primary use cases[7], which met the user needs of CapMetro as well as tested individual aspects of the TONY ADS system that were relevant to the project.

AUTOMATED USE CASES

Use Cases are the scenarios which a nominal bus would go through upon its return to the bus depot after revenue service. The use cases that were tested during Demonstration Two are as follows:

- **Automated Precision Parking-** Tests the ability of the vehicle to park precisely (=/<12") in same location over multiple repetitions.
- **Remote Start and Stop-** Tests the ability of the vehicle to turn on and off remotely using the TONY kit.
- **Automated Bus Wash Navigation-** Tests the ability of the vehicle to navigate through the bus wash using LIDAR and reduced quality GPS localization.
- **Automated Charging-** Tests the ability of the vehicle to navigate under the pantograph charger and correctly align the dispenser with the charging rails. Figure 6-9 shows the automated BEB underneath the pantograph charger after a successful approach.

Figure 6-9: The automated bus parked underneath the pantograph charger after an automated approach sequence

[7] Full use cases can be found in the appendix.

AUTOMATED FEATURES

Automated features are smaller aspects of functionality which, when combined, may comprise an automated use case. The features that were tested during the course of Demonstration Two are as follows:

- **Self-Navigation-** Tests the ability of the bus to navigate a route without sensor input aside from GPS.
- **Mode Transitions-** Tests the ability of the bus to transition in and out of automated? mode under various conditions.
- **Path Following-** Tests the ability of the vehicle to run a route with all sensors active and under nominal conditions.
- **Object Detection and Avoidance-** Test the ability of the vehicle to detect and avoid a variety of obstacles.
- **Following, Pacing, Stopping-** Test the ability of the vehicle to detect object speed and pace behind at an appropriate distance.
- **Intersections-** Tests the ability of the vehicle to navigate intersections, with and without other vehicles.
- **Robustness-** Test the ability of the vehicle to drive in automated mode in the depot for up to 30 minutes without human intervention.

Each use case and automated feature was analyzed for scenario requirements and formed the basis of each of the test cases written and carried out during Demonstration Two. During this demonstration, the primary focus was on real world scenario testing. Both hardware-in-the-loop (HIL) and integration testing were completed during PRI's internal QA testing in Virginia.

TESTING

The test methodology followed automotive and automated vehicle industry standards as well as International Organization for Standardization (ISO) 21448: Safety of the Intended Functionality. The testing contained scenarios which required the vehicle under test (VUT) to respond to situations within its operational design domain (ODD). This type of testing ensured we validated the intended functionality as opposed to fault injection testing as would be required for ISO 26262: Functional Safety. The use cases and requirements were validated by a "one to many" relationship, wherein a single use case or requirement had many test cases to validate individual aspects as well as the use case start-to-finish. Each test case was handwritten and peer reviewed by both WSP and PRI. The test conditions contained the actions which were used to place VUT into a situation which required the TONY system to divert from its nominally expected action.

The TONY system stores all logs on a secure digital (SD) card that can be removed, and the contents uploaded to any computer. After each round of testing, all results were labelled, organized, and stored. Then each test case result was reviewed and assigned a pass or fail status based upon the criteria outlined in the test conditions for that test. Tests that failed were triaged based upon the cause of their failure and the severity, not only at the system level, but also of the potential outcome in the yard. PRI and WSP reviewed the logs, and PRI was responsible for modifying or fixing the system, if needed, before the tests were attempted again.

ACCEPTANCE TESTING AND CRITERIA

The purpose of acceptance testing is to define the performance parameters for the given test activity. Similarly to how we defined the steps and expected results for an individual test case, each of which can be passed or failed, each of the two stages of Demonstration Two needed to have parameters that could be passed or failed. Criteria included both qualitative and quantitative measurements of test performance at the programmatic level, such as requirements coverage, the percentage of tests completed, passed, failed, and timeline requirements.

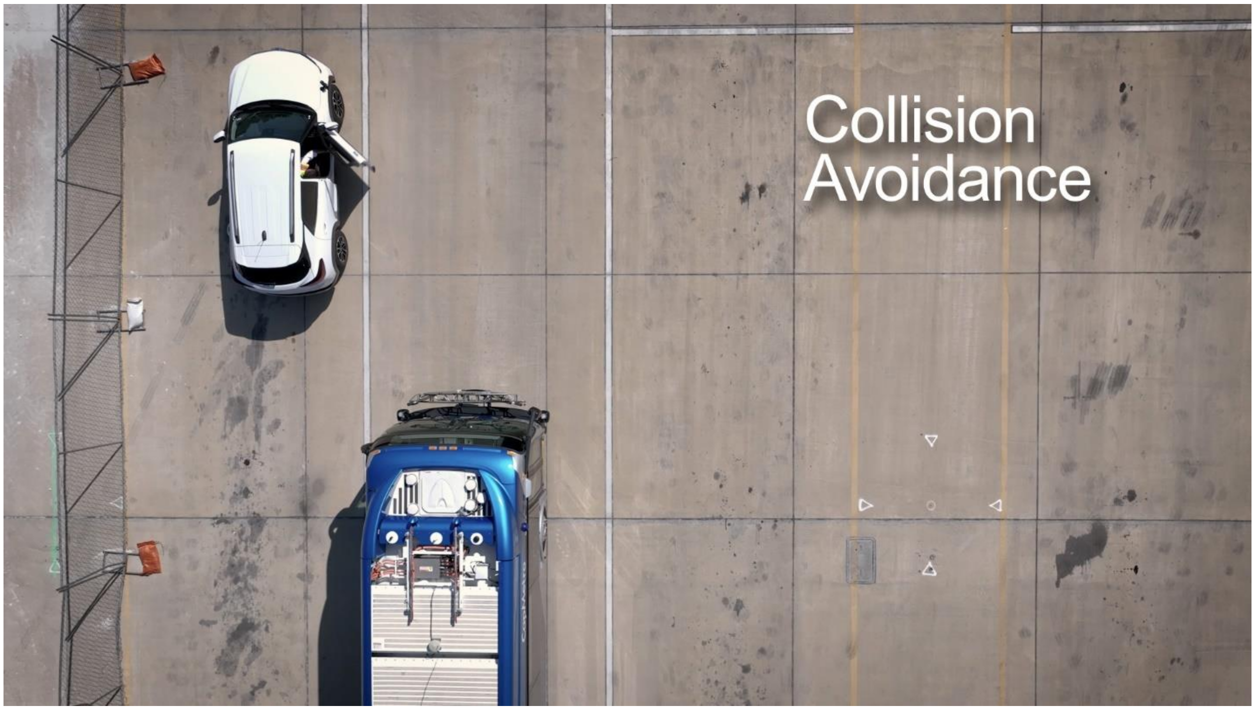
The criteria for proceeding from Stage One, With Operator, to Stage Two, Without Operator were as follows:

- 90% of executed test cases are marked as passing.
- 100% baseline functionality (self-navigation, mode transitions, path following) test cases passing.
- Written Sign off from PRI.
- Written Sign off from WSP.
- Written Sign off from CapMetro.
- All criteria above must be met to proceed to Stage Two.

RESULTS

As mentioned above, the test results of Demonstration Two can be separated into two main stages—with operator and without—four types of use cases, and six features. The test suite contained a total of 283 test cases with a roughly even distribution between all ten categories, except for object detection and avoidance which contained 90 test cases alone. An example of an object detection and avoidance scenario can be seen in Figure 6-10. The first three categories—Self-Navigation, Mode Transitions, and Path Following—were baseline functionality categories. These categories contain tests to ensure that the vehicle's main systems were working properly before moving on to other tests which could potentially carry a high risk and severity of failure. Additionally, they were tested first in order to catch any baseline system faults early before any other tests were conducted. This was done for both the safety of the team and efficiency as major software changes to baseline functionality would require restarting and retesting all test cases.

Figure 6-10: An example of a vehicle object detection and avoidance scenario being performed during testing



Since there were two categories—with operator and without—the test suite was repeated twice. As the test team executed each test case, they assigned a rating to the test case based upon the observed behavior of the system compared to its expected behavior. Those ratings can be seen in Figure 6-11 below.

Table 6-1: Test Result Expectations

Test Result	Description
Pass	The test passed. The expected results were achieved.
Fail	The test failed. The expected results were not met.
Needs Investigation	Inconclusive. There may have been a system-level action that warrants a log investigation.
Reviewed Pass	Pass resulting from a log investigation.
Defer	For one or more reasons, the test will not be executed during the testing phase.

Unfortunately, many test cases during Demonstration Two ultimately had to be deferred. Stage one had a 29.7% rate of deferral, and stage two had a 55.5% rate of deferral, leading to effective test suite sizes of 199 with operator and 126 without operator. Tests were deferred for the following reasons:

- The CapMetro North Operations bus depot layout did not support the test case as written inside the prescribed ODD (~5%)
- Onsite Staffing Issues (~5%)

- Project Time Constraints (~5%)
- Safety Considerations (~5%)
- Auxiliary Battery Issues—Explored in *Onsite Testing* below (~10%)
- Repetition of baseline tests not needed in Stage Two of testing (~25% of Stage Two testing only)

Over the course of the first stage of Demonstration two, which took place between February and June 2025, the test team completed 199 test cases with an overall pass rating of 94.97%. The 199 test cases had a breakdown of 189 passing, 10 failing, and 84 differed—Table 6-2.

Table 6-2: With Operator Test Result Breakdown

With Operator Category	Number of Tests	Pass	Fail	Defer
Self-Navigation	12	12	0	0
Mode Transitions	24	24	0	0
Path Following	21	21	0	0
Object Detection and Avoidance	90	64	6	20
Following, Pacing, Stopping	15	15	0	0
Intersections	42	24	0	18
Remote Start	21	0	0	21
Bus Wash	21	10	2	9
Charging	6	5	1	0
Precision Parking	15	9	0	6
Robustness	16	5	1	10
Total	283	189	10	84

Though some test cases did fail, the vehicle and TONY system did meet the criteria—90% of executed tests passing and 100% baseline functionality passing—to progress to Stage Two, without operator. Those results can be seen in Table 6-3.

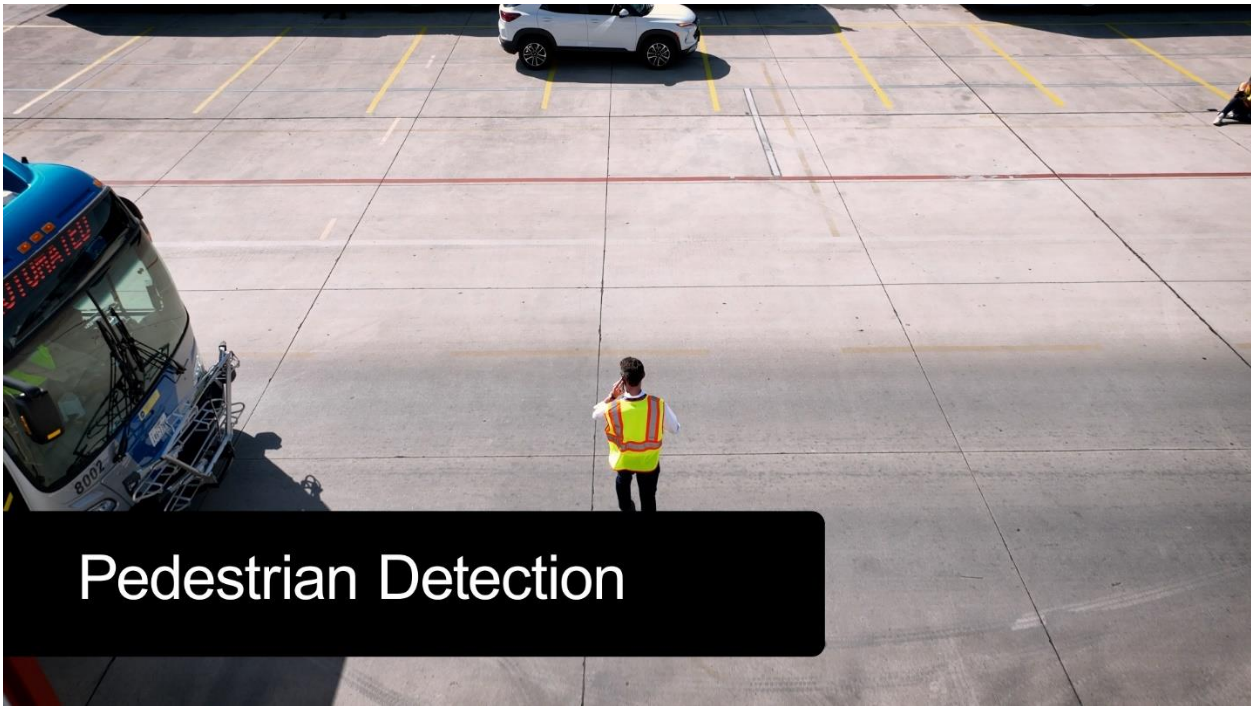
Table 6-3: Without Operator Test Result Breakdown

Without Operator Category	Number of Tests	Pass	Fail	Defer
Self-Navigation	12	9	0	3
Mode Transitions	24	21	0	3
Path Following	21	0	0	21
Object Detection and Avoidance	90	81	0	9
Following, Pacing, Stopping	15	0	0	15
Intersections	42	0	0	42
Remote Start	21	6	0	15
Bus Wash	21	0	0	21
Charging	6	6	0	0

Precision Parking	15	3	0	12
Robustness	16	0	0	16
Total	283	126	0	157

Over the course of the second stage of Demonstration Two, which took place in June 2025, the test team completed 126 test cases with an overall pass rating of 100%. An example of a pedestrian detection test executed during the second stage of testing can be seen in Figure 6-11 below[8].

Figure 6-11: An example of a pedestrian object detection and avoidance scenario being performed during testing



7. LESSONS LEARNED FROM PHASE ONE

Due to the nature of the YARD project and the innovative and cutting-edge technology involved, the project team expected many unexpected challenges to arise. This section outlines the key takeaways and insights gained throughout the duration of this project. Included is a collection of highlights of things that worked well, those that did not quite hit the mark, and most importantly how improvements are going to be made going forward. These are not just observations; they are actionable points designed to make future projects more efficient.

FUNDAMENTALS

[8] Full test cases, results, and test comments will be made available as mentioned in the Data Management Plan section.

The initial demo phase laid a strong foundation for the remainder of the project. This stage focused on mapping, proof-of-concept validation, and building confidence among stakeholders.

- **Surrogate Vehicle Mapping Was Critical.** Conducting initial mapping using a surrogate vehicle proved to be an efficient strategy, reducing time and complexity during Demonstration Two. This step allowed the team to build a highly accurate base map and validate GPS quality ahead of time.
- **Operational Flow Observations Improved Software Design.** Gaining an early understanding of the yard's bus flow, sequence of operations, and real-world behaviors gave engineers valuable insights to tailor software configurations and routing.
- **GPS Quality Checks Provided Risk Mitigation.** Performing GPS signal quality assessments during this phase allowed the team to identify areas with weak coverage, enabling better planning and troubleshooting during final implementation.
- **Stakeholder Confidence Was Elevated.** Demonstrating the feasibility of automated technology in an active transit yard environment helped build excitement and trust among CapMetro staff and project stakeholders. This was a critical step in ensuring buy-in and long-term program support.

RETROFITTING AND QA

This phase involved hardware and software integration, hardware-in-the-loop testing, and iterative refinement using the actual electric bus and Perrone's TONY autonomy system at PRI's Charlottesville, Virginia headquarters.

- **Partial System Integration Had Trade-Offs.** While avoiding a full vehicle integration saved time and preserved the Original Equipment Manufacturer (OEM) configuration, it resulted in a reliance on surrogate battery power for the TONY system. This led to voltage fluctuation issues that occasionally impacted performance and introduced troubleshooting delays.
- **EV Infrastructure Awareness Is Essential.** Infrastructure limitations in Charlottesville highlighted the importance of fully aligning all project partners on EV-specific charging requirements, including charger types, communication protocols, and software needs.
- **Steering Design Constraints Require Long-Term Planning.** Due to integration constraints, the vehicle was outfitted with an over-the-top steering mechanism. While functional, this setup occupied space in the driver's cab. Future efforts may benefit from integrating a steering solution more directly with the vehicle's steering column for a more compact and maintainable setup.

ONSITE TESTING

The final stage of the project brought the vehicle to Austin for on-site testing and demonstrations within CapMetro's operating yard. This was the most complex phase, involving real-world testing in dynamic conditions.

- **Power Supply Remained a Challenge-** Continuing to operate the TONY system from auxiliary batteries caused voltage fluctuations, leading to delays, loss of data and increased costs. A fully integrated power solution will be important for future long-term deployments.
- **Extreme Heat Affected Vehicle Testing-** HVAC issues on the bus led to uncomfortable conditions for test personnel, underscoring the need for robust climate control—especially in extreme weather environments like Texas.
- **Dynamic Yard Conditions Require Flexible Mapping-** Ongoing construction and changes in parking layout required frequent map adjustments, which consumed significant time and resources. Future autonomous yard deployments should anticipate and plan for this kind of variability.
- **Strong Collaboration with CapMetro Staff-** CapMetro's maintenance and yard personnel were instrumental in supporting successful on-site testing. Their responsiveness and hands-on assistance significantly improved the testing experience and operational uptime.
- **Charger Infrastructure Needs Attention-** Battery-electric bus chargers were occasionally inoperable or undergoing maintenance, and the overhead pantograph charger introduced new software and hardware compatibility challenges. These issues emphasized the importance of robust, well-maintained EV infrastructure for autonomy programs. Due to these potential challenges the project schedule should account for this when charging infrastructure is involved due to the complexities surrounding testing and commissioning. Additionally, an automated fleet and charging infrastructure may have significant depot design implications and, as this technology matures, it will be advantageous for agencies to incorporate automated fleet capabilities within their approach to design. Results are less effective for bus depot retrofits.
- **Manual Driving Insights Helped Future Planning-** Even when operated manually, certain yard maneuvers—like passing through the bus wash—proved more difficult than anticipated. These insights helped the team design improved autonomous logic for future versions of the system. While the project team ran several of the same routes with the cutaway bus during Demonstration One, it would have been optimal to run the same routes manually with a 40' bus to identify potential future challenges.
- **Vehicle Upkeep Will Be Critical-** The project team had the bus for over 18 months, including time away from the CapMetro depot, and did not undergo a preventative maintenance inspection from the CapMetro bus maintenance team. Going forward, for more comprehensive deployments as planned for Phase Two, the project team will work

more closely with bus maintenance to determine if, when, and how preventative maintenance and potential corrective maintenance should occur. In perfect circumstances, it would have been ideal to have the bus inspected upon return from the retrofit process in Viriginia to reduce the likelihood of mechanical failures. Luckily, the bus that CapMetro selected was less than a year old and did not undergo any significant mechanical issues throughout testing.

- **Education and Involvement-** While the first educational AV cutaway deployment was demonstrated at the beginning of the project, additional efforts to involve CapMetro stakeholders and potentially more frontline personnel may have resulted in increased engagement throughout the research and development phase. TTI was excellent throughout the project and continually demonstrated the truthful impacts of fleet automation and where positions may be impacted and additional resources required.

8. CONCLUSION

Phase One of the CapMetro Yard Automation Research and Deployment (YARD) Program was a success that yielded insightful results that will help guide clear research objectives for a Phase Two deployment. Phase Two will further explore the benefits and challenges of automating buses in the transportation yard. Below is a list of high-level achievements that align with the original goals of the FTA STAR grant program:

1) The retrofit of a New Flyer Xcelsior battery electric bus (BEB) with an Automated Driving System (ADS) achieving SAE Level 4 automation capabilities.
2) Demonstration Two, which achieved a 94.97% and 100% test case pass rating during the two exhaustive test and validation phases (with an operator and without an operator), respectively.
3) In-depth testing of automating the bus wash and documenting potential damage to sensors that may inhibit system capabilities. The ADS-equipped BEB completed the bus wash test case with no documented damage and performed the exact same route within the yard pre-wash.
4) A detailed benefit-cost analysis (BCA) produced a rating of 3.25 when accounting for all capital and operating expenses in comparison to the $164.8 million in realized benefits over 10 years.
5) Real world workforce data and requirements concluding the predicted change to 10 different operations and maintenance roles within the yard and created two additional roles to support the new ADS technology.

Additionally, the project team experienced valuable lessons learned that will not only be taken into consideration for Phase Two planning but will also provide meaningful guidance for transit agencies interested in learning more about the benefits and challenges of transit automation. Specific lessons learned are centered mainly around infrastructure planning and timing, data sharing, and include additional time for deployment testing. The support, input, and guidance from the FTA, Volpe, and stakeholders of the CapMetro Phase One project accomplished a market-first demonstration and it is the intent of the same project team to capitalize on the achievements and prove the benefits are achievable and scalable in a Phase Two deployment that will hopefully set another significant milestone for the transit industry.

APPENDIX

GLOSSARY OF AUTOMATED DRIVING CONCEPTS AND TERMS

Control

When the onboard AV computer decides to move the vehicle, those commands are sent through a gateway to the vehicle control Engine/Electronic Control Units (ECUs via the CAN (Controller Area Network) bus. The gateway translates those commands in a way that the vehicle can understand, and the vehicle control ECUs direct the actuators (braking, acceleration, and steering), motors, and electrical systems to carry out the functions thus enabling the vehicle to navigate its designated ODD (operational design) domain.

Localization

Localization is a concept in which the AV computer combines both GPS and mapping data to establish a very precise data point of where in the world the AV is currently located. GPS alone is not accurate enough for this application, so the AV will use “ground truth” data, such as lane lines, signs, mapped features, to home in even closer. Usually this will involve moving the vehicle manually, as the changes in ground truth and GPS data will help the localization process. Though recent updates to GPS and cellular towers may offer enough precision and accuracy, that movement is not necessary for this application.

Mapping

A critical precondition of enabling autonomy is mapping the identified ODD of the AV. While the AV has 360-degree viewing capabilities and GPS data to find itself in the world, it will not know where it can or cannot drive without manually mapping its intended areas to navigate first. Manually driving the operating area with lidar and radar sensors active and recording creates a digital map which can then be used as localization reference points during autonomy functions.

Object Classification

Object classification is the natural evolution of detection. By taking the object that was identified in the object detection phase, and usually applying sensor fusion as well, the AV can compute the general shape of the object. For example, even at a distance, an automotive lidar point cloud can yield results very close to the actual 3D shape of an object. The next step is to use a machine learning algorithm to teach the computer to associate those shapes with objects that it is likely to encounter on roads such as cars, bikes, pedestrians, or vegetation. Once the AV computer can identify the type of object the vehicle is detecting, different rulesets can be imposed, modifying the vehicle's behavior around that object.

Object Detection

Object detection is the core of any automated system. It refers to the ability to use sensor input to determine that there is an object nearby the vehicle. Detecting an object does not necessarily mean that it poses a threat to the vehicle, but it is a necessary precondition to being able to travel through the world efficiently and the predecessor to object classification.

Path Following

Path following is the most basic form of autonomy. This concept describes the movement that a vehicle will take once localized to accurately follow its mapped path, including road features such as stop signs and speed limits, but does not necessarily include reactions to unmapped obstacles in its path.

Perception

These are all the data streams that provide inputs to the automated vehicle (AV) computer. Cameras, lidar, radar, ultrasonic sensors, and even GPS (Global Positioning System) and IMU (inertial measurement unit) data. Together these sensors give the AV computer a complete picture of its surroundings and how the vehicle fits into them.

Planning

Using the mapping data and the data that the sensors have gathered, the AV computer can create a plan on how to navigate the real world. Using the mapping data, it can create a "macro-route" of how to efficiently get from point A to point B, abiding by speed limits, and only using certain lanes of travel, while the sensor data creates the "micro-route" by adjusting to new information not already present on the map or avoiding obstacles.

Precision Docking

Precision docking is a feature which allows the vehicle to park or "dock" in an exact spot every time. In this context, this will allow the vehicle to park precisely underneath the pantograph charger within its mechanical tolerance or close to other buses with minimal spacing in the parking lanes.

Sensor Fusion

Each sensor provides the AV with a single stream of information which allows it to draw a conclusion about what the sensor is currently perceiving. One data source alone could be enough to decide on a course of action, but by combining all perception system inputs into a universal picture for the AV computer to evaluate, it can be much more statistically confident in its decisions. For example, if radar detects a large group of people on the side of the road, the radar signature could mimic a parked car. This evaluation might cause the vehicle to drive by at a higher speed than intended, whereas applying a lidar input or camera input on top of the radar may correctly identify that there is a group of people, and the AV can take steps to treat them with caution. While this scenario is outside the ODD for this project, the concepts are still applicable. Sensor fusion is also a form of redundancy which is a critical concern when it comes to safety and automated vehicles.

Trajectory Projection

Trajectory Projection is the ability to evaluate a detected object's current speed, and linear trajectory, and based upon those values, project what it will do in the future. For example, if an object is detected as a moving vehicle and it is approaching the AV from the left at an intersection without any sign of slowing, the AV can preemptively stop to potentially avoid a collision. However, in that same scenario, if the AV detects the approaching vehicle and can determine that it will slow to a stop in the appropriate area, it can continue its own mission unperturbed.

AUTOMATED USE CASES

REMOTE START AND STOP

Remote Start and Recall		
Objective	The BEB will remotely start and drive within yard limits to its designated staging or maintenance location within the yard.	
Operational Trigger Events	Vehicle is scheduled for revenue service/maintenance or blocking a vehicle scheduled for revenue service.	
Pre-Conditions	Vehicle is off. Vehicle is in a parked bus lane. OR Vehicle is currently charging or queued to charge.	
Actors	**Actor**	**Role**
	BEB	Ego vehicle
Key Actions and Flow of Events	**Source**	**Key Actions and Flow of Events**
	SAFETY OPERATOR	Request to remotely start the BEB.
	PRI	Remotely Starts the BEB.
	PRI	Moves the BEB out of the current bus lane.
	PRI	Directs the BEB to the staging area if it is scheduled for revenue service or it’s assigned maintenance bay for service.
	PRI	If the bus is not scheduled for revenue service, it is rerouted back to its lane to resume charging or waiting to charge.
Post Conditions	Vehicle and automated systems are both in nominal condition.	

AUTOMATED BUS WASH NAVIGATION

Automated Bus Wash Navigation		
Objective	After returning from revenue service, the BEB travels to the bus wash, gets washed, and prepares to return to a bus lane for charging.	
Operational Trigger Events	Vehicle returns from revenue service and is stopped at the vehicle staging area.	
Pre-Conditions	Vehicle is parked in the staging area. Vehicle is on. Vehicle is engaged in automated mode.	
Actors	**Actor**	**Role**
	BEB	Ego vehicle
Key Actions and Flow of Events	**Source**	**Key Actions and Flow of Events**
	SAFETY OPERATOR	Direct the BEB to a specific wash bay.
	PRI	Efficiently moves the BEB into the assigned wash bay.
	PRI	Parks the BEB inside the wash bay, while cleaning is completed.
	PRI	Once the wash is complete, it moves the BEB to a staging area outside the wash bay.
	SAFETY OPERATOR	Request BEB to apply the parking brake
	NF	BEB applies the parking brake.
Post Conditions	Vehicle and automated systems are both in nominal condition.	

AUTOMATED PRECISION PARKING

Automated Precision Parking		
Objective	The bus parks precisely where it is directed with minimal gaps on all sides.	
Operational Trigger Events	Vehicle returns from revenue service, bus wash, parking, or charging.	
Pre-Conditions	Vehicle is on. Vehicle is engaged in automated mode.	
Actors	**Actor**	**Role**
	BEB	Ego vehicle
Key Actions and Flow of Events	**Source**	**Key Actions and Flow of Events**
	SAFETY OPERATOR	Request to move the vehicle to a specific bus lane.
	PRI	Moves the BEB via the most efficient path.

	PRI	Stops the BEB at the appropriate location.
	SAFETY OPERATOR	Request BEB to apply the parking brake.
	NF	BEB applies the parking brake.
Post Conditions	Vehicle and automated systems are both in nominal condition. Gaps on all sides are minimal or within tolerances.	

AUTOMATED CHARGING

Automated Charging		
Objective	The bus can park and accept a charge from the overhead pantograph charger.	
Operational Trigger Events	Vehicle returns from revenue service, bus wash, or is queued to charge.	
Pre-Conditions	Vehicle is on. Vehicle is engaged in automated mode	
Actors	**Actor**	**Role**
	BEB	Ego vehicle
Key Actions and Flow of Events	**Source**	**Key Actions and Flow of Events**
	SAFETY OPERATOR	Request to move the vehicle to a specific bus lane.
	PRI	Moves the BEB via the most efficient path possible.
	PRI	Navigates the BEB down the bus lane and stops it precisely underneath the charger.
	Pantograph	Interfaces with bus and lowers overhead pantograph charger.
	SAFETY OPERATOR	Request BEB to apply the parking brake.
	NF	BEB applies the parking brake.
	NF	Bus begins charging.
Post Conditions	Vehicle and automated systems are both in nominal condition.	

ACRONYMS

ADS- Automated Driving System
ADAS- Advanced Driver Assistance System
ATU- Amalgamated Transit Union
AV- Automated Vehicle
AWS- Amazon Web Services
BCA- Benefit Cost Analysis
BCR-Benefit Cost Ratio

BEB- Battery Electric Bus
CapMetro- Capital Metropolitan Transportation Authority
CAN- Controller Area Network
CAD- Computer Aided Design
CDC- Center for Disease Control and Prevention
CM- Corrective Maintenance
ConOps- Concept of Operations
DMP- Data Management Plan
DOI- Digital Object Identifiers
DOT- Department of Transportation
ECU- Engine/Electronic Control Unit
FTA- Federal Transit Administration
GPS- Global Positioning System
HVAC- Heating, Ventilation, and Air Conditioning
IMU- Inertial Measurement Unit
ISO- International Organization for Standardization
KPI- Key Performance Indicators
KSA- Knowledge, Skills, and Abilities
kW- Kilowatt
NTL- National Transportation Library
NF- New Flyer
NTD- National Transit Database
ODD- Operational Design Domain
OEM- Original Equipment Manufacturer
O&M- Operations and Maintenance
PM- Preventative Maintenance
PMP- Project Management Plan
PRI- Perrone Robotics, Incorporated
RTK- Real-Time Kinematic
SAE- Society of Automotive Engineers
SD- Secure Digital
SOC- State of Charge
SOTIF- Safety of the Intended Functionality
STAR- Strategic Transit Automation Research
TONY- To Navigate You
TTI- Texas A&M Transportation Institute
VUT- Vehicle Under Test
YARD- Yard Automation Research and Deployment