FTA Report No. 0258

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FEDERAL TRANSIT ADMINISTRATION

Lincoln Tunnel Exclusive Bus Lane Connected Automated Bus Proof-of-Concept Demonstration Project

PREPARED BY

Port Authority of New York and New Jersey

SEPTEMBER 2023

U.S. Department of Transportation
Federal Transit Administration

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SPONSORED BY

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1200 New Jersey Avenue, SE
Washington, DC 20590

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Metric Conversion Table

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
LENGTH				
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
VOLUME				
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
NOTE: volumes greater than 1000 L shall be shown in m^3				
MASS				
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
TEMPERATURE (exact degrees)				
^oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^oC

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14. ABSTRACT
The Port Authority of New York and New Jersey (PANYNJ) established a strategic partnership with the Federal Transit Administration (FTA) and regional stakeholders to implement a Society of Automotive Engineers (SAE) designated Level 3 (L3) connected automated bus (CAB) proof of concept (POC) demonstration project. The goal of the project was to improve the operation of the contraflow Lincoln Tunnel exclusive bus lane (XBL) along NJ Route 495, which connects the New Jersey Turnpike and NJ Route 3 to the Lincoln Tunnel (LT) and the Port Authority Midtown Bus Terminal (MBT) in New York City. The XBL POC Demonstration project demonstrated the effects of connectivity and L3 automation to determine what improvements on safety and throughput can be achieved with the application of technology on buses. Three decommissioned NJ TRANSIT MCI Coach D-45 buses were retrofitted with L3 braking and steering and throttle control capability to enable (a) automated lane keeping, (b) Cooperative Adaptive Cruise Control (CACC), and (c) automated merging. The final report summarizes the POC's approach, test results, the perspective of the CAB operator, simulation modeling findings, and lessons learned.

15. SUBJECT TERMS
Automated Driving System (ADS), connected automated bus (CAB), drive-by-wire (DBW), Dedicated Short Range Communications (DSRC), Lincoln Tunnel (LT), proof of concept (POC), Society of Automotive Engineers (SAE), user interface (UI), vehicle-to-vehicle (V2V), Exclusive Bus Lane (XBL)

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Abstract

The Port Authority of New York and New Jersey (PANYNJ) established a strategic partnership with the Federal Transit Administration (FTA) and regional stakeholders to implement a Society of Automotive Engineers (SAE) designated Level 3 (L3) connected automated bus (CAB) proof of concept (POC) demonstration project. The goal of the project was to improve the operation of the contraflow Lincoln Tunnel exclusive bus lane (XBL) along NJ Route 495, which connects the New Jersey Turnpike and NJ Route 3 to the Lincoln Tunnel (LT) and the Port Authority Midtown Bus Terminal (MBT) in New York City.

The XBL POC Demonstration project demonstrated the effects of connectivity and L3 automation to determine what improvements on safety and throughput could be achieved with the application of technology on buses. Three decommissioned NJ TRANSIT MCI Coach D-45 buses were retrofitted with L3 braking and steering and throttle control capability to enable (a) automated lane keeping, (b) Cooperative Adaptive Cruise Control (CACC), and (c) automated merging. The final report summarizes the POC's approach, test results, the perspective of the CAB operator, simulation modeling findings, and lessons learned.

Executive Summary

Operational since 1970, the Lincoln Tunnel exclusive bus lane (XBL) is a 2.5-mile contraflow lane, using a westbound (New Jersey–bound) lane along New Jersey (NJ) Route 495 to carry interstate buses eastbound (New York–bound) to the Lincoln Tunnel and the Port Authority Midtown Bus Terminal (MBT) in New York City. The XBL is the most productive highway lane in the nation carrying more than 1,850 buses and 70,000 bus passengers on the single-lane operation between 6:00 and 10:00 a.m., Monday–Friday.

Figure ES-1 *Location map*

During the weekday mornings, XBL operations are achieved by running one westbound lane in the reverse direction. Operations are managed using overhead lane use control signals, static signage, and lane markings.

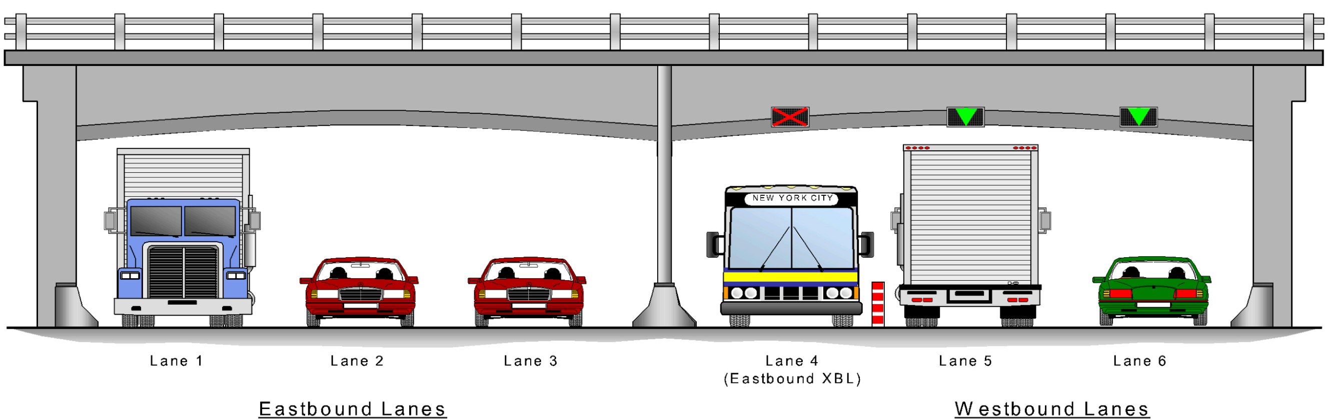


Figure ES-2 *XBL contraflow operation with lane use control signs*

The contraflow XBL operates in a physically constrained environment. It is separated from oncoming traffic by using a total of 560 cylindrical, 1.5-foot plastic traffic posts that are manually inserted into predrilled holes along the entire 2.5-mile bus lane every morning. Lane widths range from 10'4" to 12'4".

PANYNJ studies have found the XBL is beyond its peak hour capacity and has grown its passenger carrying capacity only by accommodating fully loaded buses and spreading demand beyond the peak hours to larger portions of the four-hour operation. Furthermore, any incident or deviation in traffic flow in the corridor can severely affect XBL operations as well as the general-purpose lanes through the Lincoln Tunnel causing extensive traffic backups for hours and costing millions of dollars in lost productivity, negative environmental impacts, and customer dissatisfaction. Delays have also added to travelers' concerns about the reliability of their commute, added travel time, and diminished quality of life.

The goal of the Lincoln Tunnel Exclusive Bus Lane Connected Automated Bus Proof-of-Concept Demonstration Project was to demonstrate the benefits of adopting automated driving system technologies on buses to:

1. Improve traffic flow and the effective capacity of the XBL by sustaining closer following distances and consistent speeds with the use of Cooperative Adaptive Cruise Control over its 2.5-mile length.
2. Help prevent (or mitigate the effect of) incidents and deviations in traffic flow on the XBL, which negatively affect the reliability and effective capacity of its operation.
3. Plan for the scaled adoption and deployment of effective technology solutions to enhance the safety, reliability, and effective capacity of the XBL.

Proof of Concept Results

Working with stakeholder partners New Jersey Department of Transportation (NJDOT) and New Jersey Transit Corporation (NJ TRANSIT), the project successfully tested and demonstrated effective Automated Driving System (ADS) technologies to enhance the safety, reliability, and effective capacity of the XBL. The project retrofitted three older NJ TRANSIT MCI Coach D-45 buses, deployed them, and found they were able to safely merge, maintain headway, and keep within the lane, all while allowing the operator to switch between ADS and manual modes as needed.

Table ES-1 *Bus Demand versus Throughput*

Goal	Connected Automated Bus (CAB) ADS Components
Demonstrate improvements to traffic flow and effective capacity of the XBL by sustaining closer following distances and consistent speeds over the 2.5-mile XBL.	• Cooperative Adaptive Cruise Control (CACC) • Automated Merging
Show the benefits of adopting CAB technologies to help prevent (or mitigate the effect of) incidents and deviations in traffic flow on the corridor, which negatively affect the reliability and effective capacity of XBL operation.	• Automated Lane Keeping • CACC • Automated Merging
Plan for the scaled adoption and deployment of effective technology solutions to enhance the safety, reliability, and effective capacity of the XBL.	• Automated Lane Keeping • CACC • Automated Merging
Long-term Objective	**CAB ADS Components**
Improve travel time reliability by reducing average peak hour delay by 10 minutes due to reduced incidents and breakdowns and increased throughput on the XBL.	• Automated Lane Keeping • CACC
Decrease headway to 4.5 seconds (existing average headway is 5.5 seconds) or less to support an increase in XBL throughput by 30% from the current 650 buses/hour to 840 buses/hour, effectively adding 10,000 peak-hour passengers to the 32,500 currently served.	• CACC
Eliminate delineator strikes in the contraflow XBL, thereby reducing the frequency of XBL closures due to delineators being taken out of service and having to be reset.	• Automated Lane Keeping
Increase the productivity of buses entering the contraflow XBL at its western end (the teardrop) by improving bus merging.	• Automated Merging
Enhance traffic safety on the XBL with a goal of zero collisions through CAB technologies.	• Automated Lane Keeping • CACC • Automated Merging
Reduce emissions and improve fuel efficiency due to reduced incidents and stop-and-go traffic.	• CACC • Automated Merging

The CAB Operator's Perspective

A qualitative assessment was undertaken to determine the CAB operator's response to and overall perceptions of the technology's effectiveness (i.e., extremely, very, moderately, slightly, and/or not effective) in the areas of manual and automated initiation and disengagement of Level 3 (L3) braking, steering and throttle, ease of use, understanding the information presented, whether L3 autonomy was helpful in general, and risk. The responses were generally positive, and the operators believed the automated driving system technology would be helpful in time; however, they noted that more development is needed before this type of system is put into revenue service.

Simulation Modeling Findings

Simulation modeling found increases in passenger throughput and reductions in average headways, delay and fuel savings, emission reductions, and crash reductions between the 2016 existing peak hour throughput of 650 buses per hour and the projected 2040 demand of 840 buses per hour are achievable with the introduction of ADS technology.

Lessons Learned

While the demonstration project was a success, there are still lessons that can be learned and conclusions that can be applied to deploying ADS technology into revenue service on the XBL.

1. *Refine Approach to Obstacle Detection* – Further obstacle detection refinement is required if the CABs are to stop for the smallest objects while traveling on the XBL.
2. *Refine Approach to Automated Lane Keeping* – Testing data confirm that automated lane keeping is possible on the XBL, but also suggest that further refinement of the control system is desired on the retrofitted buses. A new drive-by-wire (DBW) design and newer buses would likely overcome this issue, but alternate steering control strategies can also provide improvements.
3. *Calibration Takes Time* – Proper calibration in a complex environment like the XBL takes time. Multiple reruns are required. Retrofitted buses also perform differently from one another, each requiring their own calibration.
4. *Reflectivity Can Present Challenges to Automated Driving System Technology* – Reflectivity resulting from light rain on certain sections of pavement caused the CABs to occasionally slow down for obstacles that were not physically present. A lighting study that would recreate and demonstrate the cause of the matching issues could be undertaken to identify and implement a solution.
5. *Know the Limitations of the Selected Technology* – The selected geolocation technology had limitations. A road surface completely covered in snow, for example, would disable it. The same is true if a road surface is completely repaved or replaced, although a simple additional data collection run will resolve the issue in that case.
6. *Spend Time to Calibrate the ADS in the Operational Design Domain* – It is difficult to replicate the operational design domain on an off-site test track. While the intent is there, an exact replication is not possible. As such, additional time and effort are needed to properly calibrate a retrofitted CAB to the operational design domain prior to testing or deploying into revenue service.

7. *The Age of the Bus Matters* – Three, roughly 20-year-old NJ TRANSIT MCI D-45 Series commuter buses were retrofitted with the requisite hardware and software systems to enable ADS. There is "slop" in the multitude of parts, gearing, transmission, and torque lag associated with older combustion engine vehicles. In an ideal case, better control, more accurate response, and instant torque (no lag) would be seen with an electric bus, but the cost of an electric bus in the current marketplace is far more expensive than retrofitting a bus.

Next Steps

PANYNJ will work with the stakeholder partners NJ TRANSIT and NJDOT in establishing a working group. The working group will be comprised of subject matter experts from each respective agency and will investigate a number of different focus areas including regulatory and statutory considerations, determining desired technology applications, aligning with fleet lifecycles and procurements, and developing a plan for a scaled pilot deployment.

Section 1

Introduction

The Port Authority of New York and New Jersey (PANYNJ) established a strategic partnership with the Federal Transit Administration (FTA) and regional stakeholders to implement a Society of Automotive Engineers (SAE) designated Level 3 (L3) connected automated bus (CAB) proof of concept (POC) demonstration project. The goal of this project was to improve the operation of the contraflow Lincoln Tunnel exclusive bus lane (XBL) along NJ Route 495, which connects the New Jersey Turnpike and NJ Route 3 to the Lincoln Tunnel and the Port Authority Midtown Bus Terminal (MBT) in New York City.

Figure 1-1 *Location map*

The XBL POC Demonstration project demonstrated the effects of connectivity and L3 automation to determine what improvements on safety and throughput could be achieved with the application of technology on buses. Three decommissioned NJ TRANSIT Motor Coach Industries (MCI) Coach D-45 buses were retrofitted with L3 braking and steering and throttle control capability to enable:

- Automated lane keeping
- Cooperative Adaptive Cruise Control (CACC)
- Automated merging
- Platooning

Key stakeholders (listed below) who comprised the XBL strategic partnership were actively engaged through an Agency Advisory Group that defined operating requirements and participated in a vendor solicitation and selection process.

- PANYNJ – Operator of the Lincoln Tunnel and MBT
- NJ TRANSIT – Largest transit operator on the XBL

- Private Bus Carriers including Greyhound and Coach USA
- The New Jersey Department of Transportation (NJDOT) as a party to the operating agreement for the XBL with PANYNJ
- The New Jersey Turnpike Authority (NJTA) as a party to the operating agreement for the XBL with PANYNJ

Background

Operational since 1970, the Lincoln Tunnel exclusive bus lane (XBL) is a 2.5-mile contraflow lane, using a westbound (New Jersey–bound) lane along New Jersey (NJ) Route 495 to carry interstate buses eastbound (New York–bound) to the Lincoln Tunnel and the MBT in New York City. The XBL is the most productive highway lane in the nation carrying more than 1,850 buses and 70,000 bus passengers on the single-lane operation between 6:00 and 10:00 a.m.

During the weekday mornings, XBL operations are achieved by running one westbound lane in the reverse direction. Operations are managed using overhead lane use control signals, static signage, and lane markings.

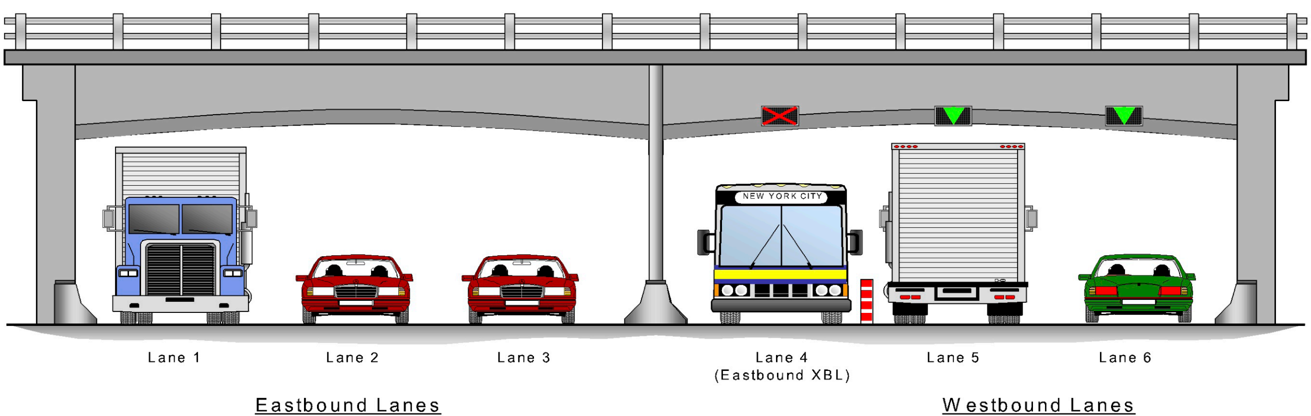


Figure 1-2 *XBL contraflow operation with lane use control signs*

Bus operators abide by the NJ TRANSIT driver’s manual as well as regulations governing the operation of motor vehicles. They also perform visual checks (e.g., determining traffic signal state, comprehending regulatory and warning signs, perceiving traffic conditions, changing lanes) and respond to audio cues (e.g., approaching emergency vehicle).

Figure 1-3 *Buses traveling on the XBL*

The contraflow XBL operates in a physically constrained environment. It is separated from the oncoming traffic by a total of 560 cylindrical, 1.5-foot plastic traffic posts that are manually inserted into predrilled holes along the entire 2.5-mile bus lane every morning. At its western end, the XBL lanes are 10'8" wide but they narrow to between 10'4" and 10'6" at various points along a 0.7-mile stretch that runs beneath the north-south local roads of Union City, NJ, through a series of eight underpasses. The XBL continues down a 0.8-mile-long elevated helix ramp to the toll plaza before entering the Lincoln Tunnel. On the helix curve, additional lane width is provided by adjusting the pylon locations, with lane widths increasing from 10'6" at the beginning of the helix to 12'4" at the southernmost point.

Current Deficiencies

PANYNJ studies have found the XBL is beyond its peak hour capacity and has grown its passenger carrying capacity only by accommodating fully loaded buses and spreading demand beyond the peak hours to larger portions of the four-hour operation. Furthermore, any incident or deviation in traffic flow in the corridor can severely affect XBL operations as well as the general-purpose lanes through the Lincoln Tunnel; thus, incidents with buses in the tunnel have caused extensive traffic backups for hours, costing millions of dollars in lost productivity, negative environmental impacts, and customer dissatisfaction. Delays have added to travelers' concerns about the reliability of their daily commute, added travel time, and diminished quality of life.

Table 1-1 *Bus Demand versus Throughput*

		Buses/Hour	Average Headway (seconds)		Delay (minutes/bus)
Existing (2016)	**Throughput**	650	5.5	Current	10
	Demand	730	4.9	Required	0
Future (2040)	**Demand**	840	4.3	Required	0

Despite substandard lane widths, tight geometries, and difficult sun glare conditions at certain times of year, the XBL has maintained an excellent safety record in 52 years of operation. Growing demand, along with longer and wider bus designs, have heightened attention to the safety, efficiency, and associated reliability of the operation.

The Midtown Bus Terminal is being replaced to overcome its current structural and capacity limitations and to ensure it can continue to serve its ridership in the coming decades. The new terminal will help support the continued growth of the regional and national economy by providing access to jobs, connecting people to destinations around the region, and offering an equitable transportation option. It will include innovative technologies and solutions such as electric bus charging opportunities, real-time information for performance-based transit operations, and traveler information systems to offer a more consistent passenger experience. The new MBT is anticipated to open by 2033 and will be supported by the XBL during the morning rush.

The Lincoln Tunnel Helix is being replaced to overcome its current structural, safety, and capacity limitations and to ensure it can continue to accommodate its ridership in the coming decades as the main feeder to and from the Lincoln Tunnel in New Jersey. It will help support the continued growth of the regional economy by providing access to jobs and connecting people to destinations around the region. The new helix will include innovative technologies and solutions including state-of-the-art over height detection systems, an upgraded XBL that has a higher capacity and reliability since it will run with the inbound traffic, real-time information for performance-based transit operations, and traveler information systems to provide a more consistent user experience. The new helix is anticipated to open in 2032 and will support the new bus terminal.

XBL CAB Demonstration Project

The XBL offers a unique opportunity to demonstrate the benefits of bus fleet automation within a heavily utilized highway transit lane in an urban setting. Even though only a few vehicles were automated for the proof of concept, it is envisioned that this demonstration will drive a technology deployment strategy for equipping vehicles using the XBL and help to inform the design plans for the MBT Redevelopment to ensure support for future connected and automated vehicles.

The project has demonstrated the effects of connectivity and automation as applied to the XBL to determine what improvements on throughput and safety can be achieved with the application of technology on buses. From west to east, there are four primary locations on the XBL where CAB technology may enhance safety and throughput. The XBL locations are:

1. Teardrop and western XBL entrances – The focus here is regarding automated merging to increase bus throughput at the entrance of the XBL.
2. Contraflow lane from the teardrop through the Union City cut (outlined in yellow in Figure 1-4) – This location is after the teardrop and is where the single-lane XBL begins. CACC was demonstrated to overcome inclining roadway grades as a primary concern, in terms of achieving capacity and safety objectives. Secondarily, lane-keeping improvements will address reliability in this section of the XBL.
3. Contraflow lane from the Union City cut to the Lincoln Tunnel Helix – This section of the XBL corridor is separated from oncoming traffic by plastic delineators. The roadway has 10-foot-wide lanes, making lane-keeping improvements critical for safety and reliability objectives.

Figure 1-4 *XBL on the Palisades approaching the helix*

4. Lincoln Tunnel Helix – The primary focus in this location is lane-keeping in terms of achieving reliability and safety objectives. It also has conflicting lane striping around the turns of the helix and passing through the toll plaza to the tunnel entrance.

As current State of New York automated vehicle regulations differed from the State of New Jersey, the demonstration project was conducted in New Jersey only and ended at the Lincoln Tunnel's toll plaza just before the New Jersey portal.

Figure 1-5 *End of XBL CAB demonstration project at the Lincoln Tunnel New Jersey portal*

Section 2

Project Goals, Timeline, and Budget

The XBL CAB Demonstration project was intended to provide a limited research environment. The project had certain needs for evaluating the technology and gaining knowledge/experience to assist in future XBL deployments. On this basis, the project selected proven vendors with outfitting automated technology and applications for deployment on a larger scale.

The goals of the demonstration project were to:

- Demonstrate improvements to traffic flow and effective capacity of the XBL by sustaining closer following distances and consistent speeds over the 2.5-mile XBL.
- Show the benefits of adopting CAB technologies to help prevent (or mitigate the effect of) incidents and deviations in traffic flow on the corridor, which negatively affect the reliability and effective capacity of XBL operation.
- Plan for the scaled adoption and deployment of effective technology solutions to enhance the safety, reliability, and effective capacity of the XBL.

The long-term objectives for equipping XBL buses with CAB technologies are to:

- Improve travel time reliability by reducing average peak hour delay by 10 minutes due to reduced incidents and breakdowns and increased throughput on the XBL. Crashes, mechanical failures, and delineator hits occur frequently costing nearly $250K per incident in lost productivity.
- Decrease headway to 4.5 seconds or less to support an increase in XBL throughput by 30% from the current 650 buses/hour to 840 buses/hour, effectively adding 10,000 peak-hour passengers to the 32,500 currently served.
- Eliminate delineator strikes in the contraflow XBL, thereby reducing the frequency of XBL closures due to delineators being taken out of service and having to be reset by improving safety for customers.
- Increase the productivity of buses entering the contraflow XBL at its western end (the teardrop) by improving merging of buses entering the XBL.
- Improve traffic safety on the XBL with a goal of zero collisions through CAB technologies.
- Reduce emissions and improve fuel efficiency due to reduced incidents and stop-and-go traffic.

With the project's goal to evaluate technology to enhance the efficiency, safety, and throughput of the XBL, its data collection was focused on measuring these types of benefits for the system.

Timeline and Budget

In 2018, FTA published its Strategic Transit Automated Research (STAR) Plan, which outlined FTA's five-year research agenda on transit bus automation. As part of the Transit Bus Automation Strategic Partnerships area, FTA partnered with several transit providers through the University of South Florida's Center for Urban Transportation Research

The PANYNJ was awarded a Strategic Partnership Grant in fall 2019 to support the XBL CAB Demonstration project. The Strategic Partnership Grant supports the collection, analysis, identification of lessons learned, knowledge transfer, and preparation of a final report. Project partners and their roles are summarized in Table 2-1 and the budget is summarized in Table 2-2.

Table 2-1 *XBL CAB Demonstration Project Partners and Roles*

Project Partner	Role
PANYNJ	Provider of MCI D-45 Series buses
NJDOT	Regional XBL partner
NJTA	Regional XBL partner
NJ TRANSIT	Provider of professional bus operator trainers to operate the CABs during the project
Southwest Research Institute (SwRI)	Provider and integrator or SAE L3 CAB ADS
Autonomous Stuff	Provider and deployer of bus sensors and hardware
New Eagle	Provider and integrator of DBW technology
HNTB	Developed POC concept of operations, systems requirements, and evaluation criteria
KLD Engineering	Developed simulation modeling

Table 2-2 *XBL CAB Demonstration Project Budget*

Project Costs	Amount
Southwest Research Institute	$1,475,000
PANYNJ Project Management and Engineering Support	$300,000
Subtotal	$1,775,000
FTA Strategic Partnership Grant	$250,000
Local (PANYNJ) Match	$62,500
Subtotal	$312,500
Total Project Cost	$2,087,500

Three, roughly 20-year-old NJ TRANSIT MCI D-45 Series commuter buses were retrofitted with the requisite hardware and software systems to enable automated lane keeping, automated merging, and Cooperative Adaptive Cruise Control. Notice to proceed was issued on January 26, 2021. The PANYNJ transferred the buses to New Eagle in Ann Arbor, MI, by February 8, 2021, where they were retrofitted with a custom aftermarket drive-by-wire system.

Given the age of the buses, bus inspection was undertaken and the remediation of issues (e.g., oil pump and battery replacement, mechanical breakdown, etc.) was completed by April 12, 2021. A relationship with an MCI Coach certified mechanic to schedule and repair the buses if a breakdown would adversely impact their retrofitting or operation throughout the remainder of the project was also established.

Upon completion of inspection and addressing some remediation issues, a three-step process was followed to retrofit the buses with ADS technology. First, DBW capability was added to perform vehicle functions traditionally achieved by mechanical linkages. This technology replaces the traditional mechanical control systems with electronic control systems that are needed to support SAE L3 automated driving. Risk levels and start dates for major milestones for each of the three areas are summarized in Table 2-3.

Table 2-3 *DBW Bus Retrofit Milestones and Risk Levels*

DBW Installation Milestones	Risk Level	Bus 1	Bus 2	Bus 3
Hardware Design	Low	02/08/2021		
Software Design	Low	02/28/2021		
Software Development	Low	02/28/2021		
Hardware Design Approval	Low	03/29/2021		
Hardware Procurement	Medium	04/08/2021		
Hardware Integration	Medium	04/13/2021	07/05/2021	07/19/2021
Software Integration	Medium	04/19/2021	07/19/2021	08/02/2021
Software Acceptance Testing	Low	05/24/2021	08/02/2021	08/16/2021
Bus Delivery to Autonomous Stuff in Moline, IL	Low	07/12/2021	08/09/2021	08/23/2021

Next, Light Detection and Ranging (LiDAR), radar, vision cameras, and other hardware to support dedicated short-range radio (DSRC) communications and data collection were specified by Southwest Research Institute (SwRI). The installation, integration, and acceptance testing of some of the hardware was performed by AutonomouStuff at their facilities in Moline, IL, between July 14 and September 28, 2021, and then the buses were transferred to SwRI in

San Antonio, TX, for the third and final step—location system installation and software integration to enable automated lane keeping, automated merging, and CACC. That work was undertaken and completed between September 8 and November 9, 2021.

Off-site testing was done at SwRI's test track in San Antonio on December 6–7, 2021. Refinements were made and tested again March 15–17, 2022, prior to deploying the CABs on the XBL. In advance of the testing, the buses were registered with the State of New Jersey to allow for their legal operation on state roads. Testing for the on-site (XBL) demonstration was performed July 16–17 and 22–23, 2022, between 12:30 a.m. and 5:30 a.m.

Section 3

Conversion Description

Background and a description of the work required to retrofit the buses to support ADS is set forth in this section.

Drive-by-Wire

The buses provided by PANYNJ did not have DBW systems installed, which are required for ADS. Figure 3-1 illustrates the high-level approach taken to retrofit the buses with DBW capability.

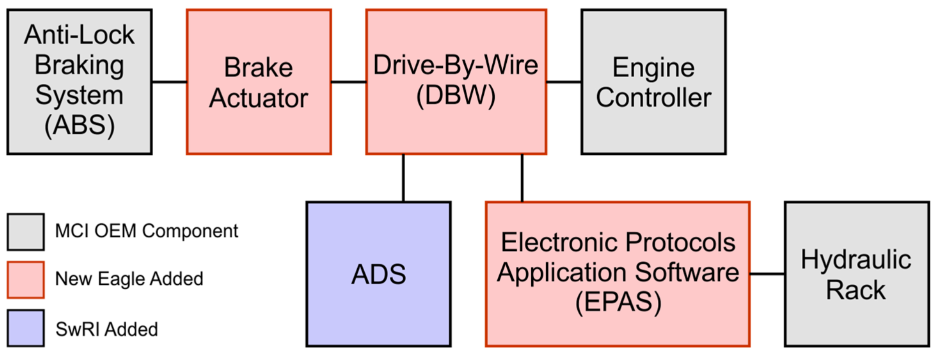


Figure 3-1 *Drive-by-wire bus retrofit overview*

Drive-by-wire replaces the traditional mechanical and hydraulic control systems with electronic control systems using electromechanical actuators and human–machine interfaces such as pedal and steering feel emulators. In order to retrofit the XBL CAB Demonstration project buses, Robot Operating System (ROS) nodes, a set of software libraries and tools for building robot applications, were developed to integrate with each bus's Controller Area Network (CAN). ROS nodes are used in different areas, from humanoid robots to industrial robots and autonomous vehicles. The Robot Operating System includes mature open-source libraries to be used for navigation, control, motion planning, vision, and simulation purposes. The CAN bus is a robust vehicle bus standard designed to allow microcontrollers and devices to communicate with each other's applications without a host computer. ROS nodes simplify integration by handling CAN translations. From here, steer-by-wire (SBW), brake-by-wire (BBW), and accelerator-by-wire (ABW) integration was developed to set the stage for ADS.

Steer-by-wire eliminates the physical connection between the steering wheel and the wheels of a bus by using electrically controlled steering actuators to change the direction of the wheels and to provide feedback to the driver. A steering actuator was mounted upstream of the existing hydraulic assist to replicate human torque input, and for detecting bus operator input for canceling out steering wheel inertia to mitigate false overrides. A stress analysis was also conducted to ensure the steering actuator could be properly supported on the bus. The bus retrofit was designed to enable the CAB operator to retain steering control when the steering actuator became disabled or through an electronic stop.

Brake-by-wire technology has been widely commercialized with the introduction of battery electric vehicles and hybrid vehicles. The technology supplements traditional components such as pumps, hoses, fluids, belts and vacuum servos, and master cylinders with electronic sensors and actuators. A pneumatic valve was installed upstream of the automatic braking system valve. This approach retained all the factory automatic braking system (ABS) functions on each bus. The valve contained dual controllers for the front and rear brakes to provide redundancy and was deployed on each bus and tied into the brake lines with a shuttle valve. This allowed the CAB operator to override the command of the ABS controller as needed. Similar to the SBW motor device, the bus retrofit was designed to enable the CAB operator to retain steering control when the pneumatic valve became disabled or through an electronic stop.

Accelerator-by-wire technology measures how much or how little the bus operator moves the accelerator, and the sensors send that information to the engine management system. An accelerator interface device was deployed on each CAB to automate this manual function. Similar to the SBW steering actuator and BBW pneumatic valve, the bus retrofit was designed to enable the CAB operator to retain steering control when the accelerator interface became disabled or through an electronic stop.

DBW regression testing confirmed that repeatable CAB speed, steering, accelerator, braking, and shifting commands were successfully sent and received. The following tests were conducted.

- Stationary Functional Tests that enabled and disabled SBW, BBW, and ABW components.
- Stationary and Moving Override Tests that validated CAB operator overrides of SBW, BBW, and ABW components.
- Moving Functional Tests that enabled, actuated, and disabled SBW, BBW, and ABW components.
- Stationary Performance Tests that tested a mixture of SBW, BBW, and ABW inputs.
- Moving performance Tests that tested a mixture of SBW, BBW, and ABW components in off-site and real-world conditions.
- Fault Injection Tests to evaluate communication failures and high-frequency data exchanges.

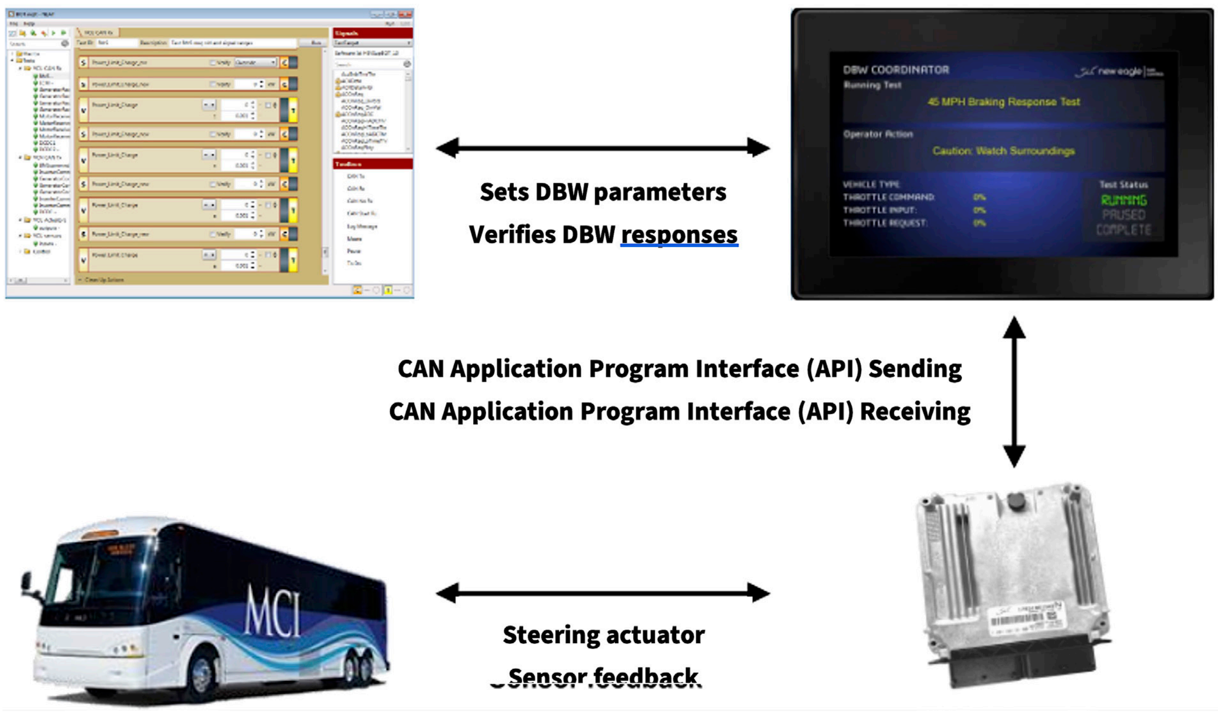


Figure 3-2 *Drive-by-wire testing overview*

L3 CAB Technology

Commonly available commercial market-ready LiDAR, radar, cameras, and miscellaneous supporting equipment that is available in today's marketplace were used to retrofit the buses. A user interface (UI) for bus operators and hardware to facilitate DSRC communications were also deployed.

Table 3-1 *CAB Hardware Overview*

Function	Hardware
Sensing	• Two Ouster OS0 LiDAR 360° mid-range environmental sensors • One forward-facing Livox Horizon LiDAR long-range environmental sensor • One forward-facing Smartmicro radar mid-range environmental sensor
Localization	• SwRI Ranger system (x1 system; x2 cameras) – map-based localization system • Global Positioning System (GPS) (x1 receiver; x2 roof-mount antennas) – provides absolute position data • Inertial Measurement Unit (IMU) (x1) – provides linear and angular velocity and accretion data
Communication	• DSRC radio (x1 radio; x2 roof-mount antennas) – provides vehicle-to-vehicle (V2V) communications between buses • 4G cellular antenna (x1) – provides general network connectivity

Figure 3-3 shows a generalized hardware diagram with placement of individual components on each CAB with the same components in three-dimensional space with associated coordinate frames.

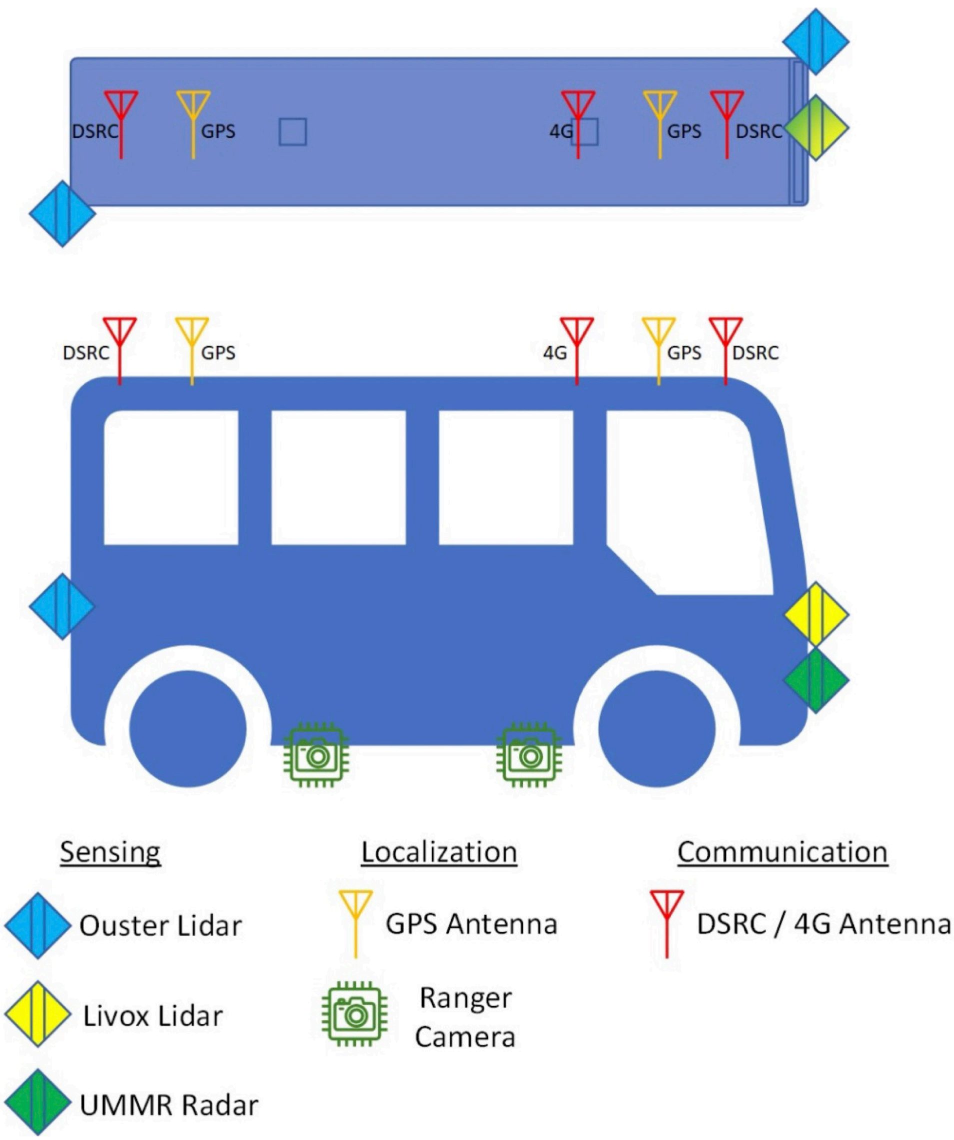


Figure 3-3 *General CAB hardware layout*

Automated Lane Keeping

Delineators between the contraflow eastbound XBL and westbound NJ Route 495 general purpose traffic lanes do not align with the painted lane lines for a portion of the facility. As such, conventional sensors and vision-based lane keeping techniques that detect the lane lines, measure their position relative to the vehicle, and provide lateral control via a feedback mechanism are not viable. Furthermore, the XBL widens around the helix until it stretches into the adjacent lane, with the boundary marked by three- dimensional delineators instead of painted lines. Traditional vision- based lane keeping will also fail in this section of the XBL. Lane lines are clearly visible but misleading at the beginning and end of the helix and absent during the majority of the turn. Other lane keeping methods must be used.

To mitigate this issue, SwRI deployed their Ranger solution as the primary localization modality to maintain lateral control, which is essential for automated lane keeping. Ranger is a high- precision localization system for ground vehicles that performs map- based localization using a ground-facing camera. Ranger uses commercially available hardware including a camera, lights, and a computer, in combination with auxiliary localization sensors and a custom state estimator, to produce a complete high- precision positioning solution suitable for feedback control of an automated vehicle. Ranger was originally conceived and designed to address the accuracy and availability problems of GPS and can operate independently from or as a supplement to GPS and other global navigation satellite positioning systems.

Ranger position measurements are made by matching live ground imagery to imagery stored on a map. The image matching process uses a feature- based approach that yields a high positive match rate with a vanishingly small false positive rate. Additional details may be found in the Institute of Electrical and Electronics Engineers (IEEE) Position, Location and Navigation Symposium (PLANS) paper, “Ranger: A Ground facing Camera- based Localization System for Ground Vehicles,” by Kristopher Kozak and Marc Alban (April 2016).

Each bus was equipped with two Ranger kits. One was installed near the rear axle and one near the front axle. A circular hole was made in the frontmost and rearmost luggage compartments to install the Ranger camera and light emitting diodes (Figure 3-4). This approach provided flexibility in calibrating the Ranger camera height and facilitated system installation without having to get underneath the bus.

Figure 3-4 *Ranger deployment location*

Ranger has numerous advantages over other traditional methods of lateral control, and:

- Works on a wide variety of road surfaces including asphalt, cement, and concrete, as well as hard packed gravel and dirt.
- Does not rely on painted lane lines so it cannot be confused when lines are absent or misleading, or when they change or fade.
- Does not rely on forward- facing vision systems so it cannot be blinded by the sun at low angles in the sky.
- Is robust to up to 60% occlusion of the road surface so even significant amounts of dust, dirt, leaves, or other detritus will not impair its operation. Ranger is also robust to wet surfaces, both during and after precipitation.
- Is an inexpensive, robust system, relying on only a downward- facing camera, a series of lights, and a processing unit.

Cooperative Adaptive Cruise Control (CACC)

Longitudinal control is the second major component of the basic driving task. Standard cruise control, simply maintaining a desired speed, is of course insufficient. Adaptive cruise control (ACC), which attempts to maintain a desired target speed while also maintaining a minimum desired headway to the leading vehicle, is the correct tool for this task. The specifics of the XBL corridor pose only a few new difficulties for the ACC system.

The first potential difficulty is the desired density of buses. Due to the geometry of buses—with tall, wide, flat backs—as density grows and headway shrinks, the profile of the leading bus available to sensors on the CAB fills the field of vision, potentially frustrating vehicle classification algorithms. In other words, if the ACC algorithm is attempting to classify the leading object as a vehicle, it may not be able to do so when the buses are closely packed.

The second potentially difficult area is the helix turn on the XBL. The turn is tight, so if buses are densely packed, the view of the leading bus is skewed, and if buses are not densely packed, the view of the leading bus is obscured by the turn. The ACC system must account for the high curvature of the path during that section.

The CABs were retrofitted with several sensing modalities to enhance ACC to create CACC.

- Radar was installed to provide sufficient information along the majority of the XBL to maintain a safe headway to the immediate leading vehicle.
- A vision- based vehicle identification system was installed to provide both additional information about the immediate leading vehicle and supplemental data about the entire scene in front of the bus.
- Front- facing LiDAR supplements the radar as a redundant modality with higher spatial resolution but lower relative velocity certainty.
- Vehicle-to-vehicle (V2V) connectivity over DSRC was installed to enable the CAB to incorporate accurate position and velocity information not only from the immediate leading vehicle, but also from vehicles farther ahead to rapidly respond to changes in the traffic pattern. This V2V connectivity will enhance the ACC system to create a CACC system.

Figures 3-5 through 3-7 show the location of the devices on the connected automated buses.

Figure 3-5 *Radar and vision camera on the front of the CAB*

Figure 3-6 *Side-facing LiDAR on the front of the CAB*

Radar, LiDAR, and vision perception sensors allow the CAB to maintain the appropriate headway to the vehicle in front of it. However, this headway will be bounded by safety considerations. If only the immediate leading bus is known, then the CAB must maintain sufficient separation to decelerate or stop in response to its behavior. However, if in addition to the immediate lead vehicle, information about vehicles farther forward is known through V2V communication, then the CAB can potentially decrease its headway even further without sacrificing safety.

A CAB with a DBW system and a high- precision localization system to enable consistent lateral positioning enables the CACC to increase XBL throughput. Accurate and robust perception of the immediate leading vehicle allows the CAB to control its headway to the next bus, adjusting density as desired within appropriate safety margins. Additionally, localizing the vehicles farther ahead through DSRC permits it to maintain speed with confidence.

Note the side-facing LiDAR in the front and rear of the CAB was mounted in a manner that did not exceed the mirror-to-mirror width of the bus. This approach minimizes the possibility of LiDAR being hit when the CAB is in service. LiDAR was also positioned in a manner that enables the CAB operator to see when the CAB's turn signal has been activated.

Figure 3-7 *Side-facing LiDAR on the back of the CAB*

Automated Merging

Merging automated vehicles into nearby traffic has been an ongoing area of research across the industry for years. The challenges to deploying a solution to the general case of this problem center on robustness to the variable driving environments found throughout the U.S. road system. In addition to difficult or complex road geometries, any practical general solution would need to handle situations involving aggressive and intentionally disruptive manually driven vehicles, roadway disruptions such as work zones, and the wide range of environments in which merges take place.

To reduce the complexity of the situation without reducing the applicability of the demonstration project, automated merging was limited to merging a single CAB and two other buses, either automated or manually driven. The CAB makes the decision to merge ahead, between, or following the other two vehicles based on its analysis of merge safety. In particular, the position, speed, and spacing of the other two buses are evaluated to determine the best placement of the merging CAB. The manually driven vehicles, if any, will drive within the expected parameters outlined in the individual merge scenario descriptions. Divergence from these parameters intentionally or unintentionally will cause a different scenario to occur, or a safe stop of the CAB if no scenario criteria can be met.

Combining the strengths of DSRC and side-facing LiDAR gives the CAB a clear view of the merge target lane, allowing it to decide about merge strategy in certain situations. Because DSRC provides accurate, high-availability, frequent updates about the CAB's position and velocity, the target lane can be scanned via radio for vehicles that would interfere with merging. Side-facing LiDAR sensors provide the necessary spatial resolution and range to identify gaps between vehicles in adjacent lanes, in particular the target lane of the merge. These sensors do not rely on other buses having been equipped with any technology; however, they are limited by line-of-sight considerations, while DSRC is not.

User Interface

Society of Automotive Engineers (SAE) L3 is a mode in which all aspects of driving are handled for the vehicle operator, but the operator must be present at all times in case an intervention request is made. For an SAE L3 automated system to be useful, the operator must not only trust its operation, but also be confident in its abilities and comfortable with its interactions. The SAE Standard J3016 defines six levels of driving automation (Figure 3-8).

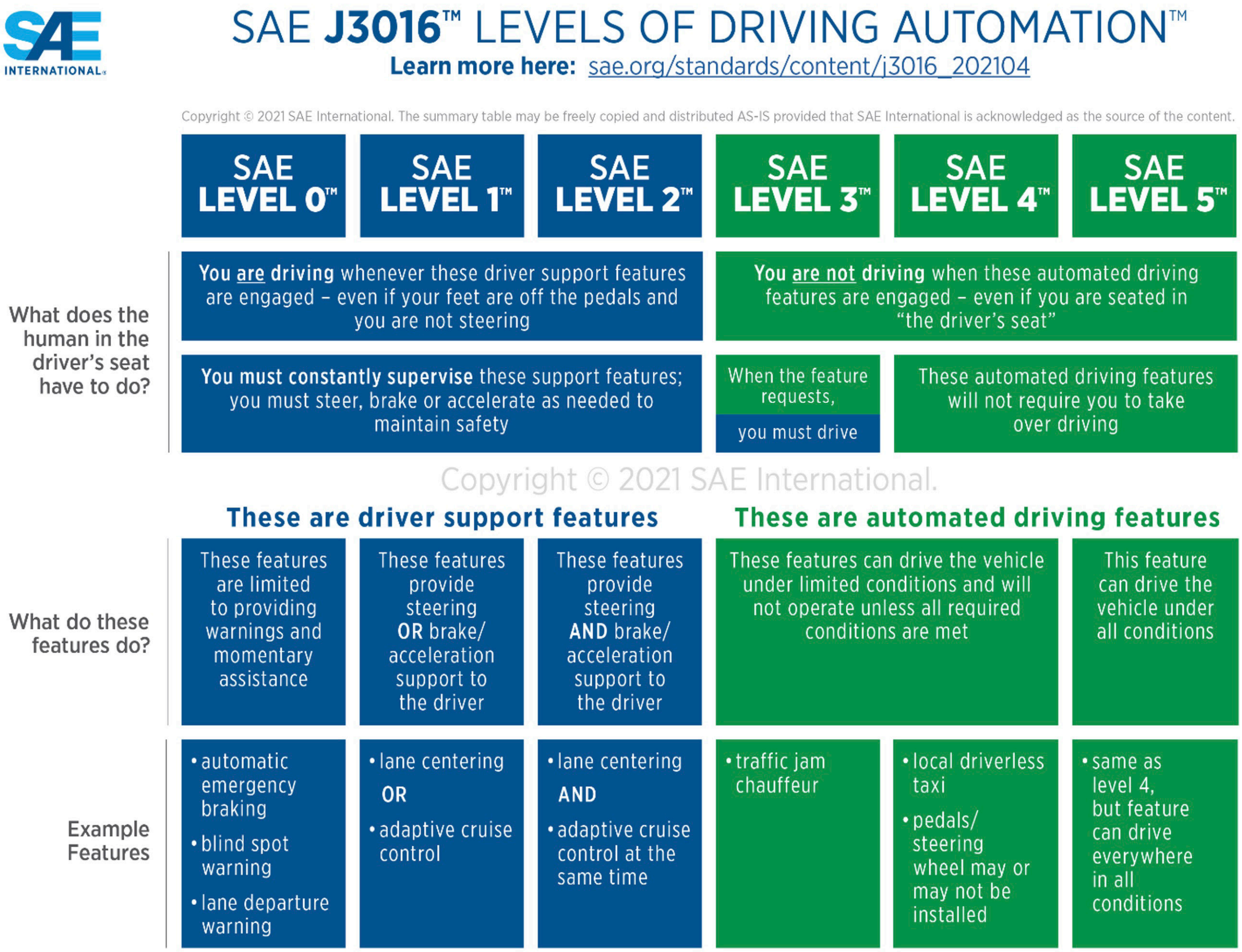


Figure 3-8 *Society of Automotive Engineers (SAE) levels of driving automation*

A simple, intuitive two-part CAB operator UI was developed and deployed to improve safety and operator trust in the automated driving system. Sufficient data as well as simple engagement and disengagement interfaces were provided to the operator in a UI without overwhelming the operator with extraneous information.

The first part of the UI is the physical interaction of the CAB operator with the ADS for the purpose of engaging and disengaging the system. A simple physical momentary switch, mounted for fast, convenient access by the operator both to engage and disengage the system, was deployed on each CAB. The second part was a touch- screen tablet- based operator interface that communicates the state of the ADS to the CAB operator. It also provides the ability to modify system configuration parameters.

Figure 3-9 *Position of the CAB user interface*

Miscellaneous Hardware

The onboard radio unit to facilitate DSRC communications was housed behind the CAB operator seat. The requisite hardware to support integration of DSRC communications, LiDAR, radar, cameras, and UI were also installed behind the CAB operator seat.

Cabling

All cabling and wire management was orchestrated through the vehicles' luggage racks.

Figure 3-10 *CAB cabling scheme*

Software

SwRI integrated its proprietary autonomy software suite onto the buses. The software suite leverages the ROS middleware and was developed internally at SwRI. The software architecture is generally broken down into the following subsystems:

- Perception/LiDAR – The collection of modules tasked with ingesting and processing data from LiDAR (and potentially other perception sensors). This includes segmentation of the ground/driving surface and non-ground objects-of-interest from raw sensor data. Outputs include a list of relevant objects for consideration by path and speed controllers.
- Localization – The collection of modules tasked with ingesting and processing data from a variety of localization data sources, including SwRI's Ranger system, GPS, and other inertial sensors such as IMUs, gyroscopes, and wheel speed encoders. Outputs include estimates of current vehicle position, orientation, and speed, as well as a variety of coordinate system transforms that can be used to translate data from one coordinate system to another.
- Path Control – The collection of modules tasked with evaluating current driving conditions to control speed and steering commands. Speed commands are determined from a variety of inputs, including target speed (i.e., speed limit), route curvature, and lead objects, among others. Steering commands are generated to keep the vehicle on a desired path (generally centered in the lane of travel).
- Routing – The collection of modules tasked with generating a high-level route for the vehicle to follow. This includes a custom web-based UI allowing the operator to select a desired destination on a map, as well as algorithms to calculate intermediate points for the vehicle to follow between the current position and desired destination, monitor the vehicle's progress along the route, and update the route if required.
- Miscellaneous – The collection of additional modules with varying purposes such as visualization tools and a "black box" data recorder.

Appendix A shows the software architecture diagrams.

There are additional software modules for passing, steering, throttle, and brake commands to the DBW for actuation, as well as publishing feedback (e.g., current steering, throttle and brake commands) from the DBW as part of the controller feedback loop that were developed.

Section 4

Testing and Operations

Off-site testing occurred at SwRI's test track in San Antonio, TX, on December 6–7, 2021, and March 15–17, 2022, prior to deploying the CABs on the XBL to conduct the demonstration project. On-site (XBL) testing occurred on weekends—July 16–17 and 22–23, 2022, between 12:30 a.m. and 5:30 a.m.—when the XBL was closed to all other traffic not participating in the project.

Data were obtained directly from the CABs (i.e., "black box" approach) to measure impacts and assess how effectively the vehicles met the demonstration project evaluation criteria. Specific data are highlighted in the following test sections and supporting tables.

Off-site (SwRI Facility) Testing

Testing for the off-site demonstration was performed at SwRI's test track, a 1.1-mile paved test track that includes a fully signalized intersection, an on- and-off ramp, long straightaways for high- speed operation, and aprons on either end for complex maneuvers.

Figure 4-1 *Off-site (SwRI facility) test track*

The test track was set up to simulate the start/stop zones of the XBL route, where CAB operators will manually engage ADS functions upon entering the XBL and where the system will automatically disengage upon exiting the route. The off-site facility had a single merge location and a defined autonomous region. Autonomy outside this region was not possible and the route was manually driven.

Route mapping and calibration needed to generate the Ranger map was developed for the test track. Figure 4-2 shows the lane map for the demonstration and the defined autonomy region. The black outline denotes the autonomous region, the yellow circle denotes merge location, and the red circle denotes the end of the autonomous route. A speed limit of 15 miles per hour (mph) was applied to the merging autonomy region and a speed limit of 35 mph was applied elsewhere in the autonomy region. To match the bollards and concrete barriers of the XBL, SwRI added Jersey barriers and cones spaced at 11'6" along a section of the test track.

Figure 4-2 *Off-site (SwRI facility) test track autonomous regions*

On-site (XBL) Testing

Testing for the on-site demonstration was performed on July 16–17 and 23–24, 2022, on the XBL between 12:30 and 5:30 a.m. Route mapping and calibration needed to generate the Ranger map was developed early in the project and updated in July 2022 prior to the on-site demonstration. Figure 4-3 shows the lane map for the demonstration and the defined autonomy region. The autonomous region ended after the helix and before the Lincoln Tunnel toll plaza. The shorter region was selected to maximize the number of CAB runs along the XBL during the limited time frames that were available on Saturday and Sunday mornings.

Figure 4-3 *On-site (XBL) autonomous regions*

For the on-site tests, CABs were operated by NJ TRANSIT bus supervisors. These individuals have significant experience driving the XBL in all conditions and were therefore critical to assure the safe operation of the test vehicles in live traffic. A speed limit of 15 mph was applied to the teardrop region to match its average operating speed. Based upon the sway observed in the CABs at 35 mph during the off-site demonstration and the data collected and evaluated, it was determined that 25 mph would be the highest speed limit at any given location along the XBL during the on-site demonstration. Twenty-five mph was used between the teardrop and the JFK Boulevard overpass, 18 mph was used between the JFK Boulevard overpass and the beginning of the helix (because the Ranger lane map struggled to perform during periods of light rain on certain sections of XBL pavement), and 15 mph was used between the helix and the end point of the demonstration project.

A lot of preparatory work was undertaken in advance of the on-site (XBL) testing in late June 2022. SwRI performed CAB check-out testing June 25, 2022. CAB calibration was completed June 26–27, 2022, followed by NJT bus operator driver training on June 28–29, 2022.

Table 4-1 *Preparation Work for the On-site (XBL) Testing*

<table>
<tr><th>Time</th><th>06/26/2022</th><th>06/27/2022</th></tr>
<tr><td>1:00 a.m.</td><td>Move buses to staging area</td><td>Move buses to staging area</td></tr>
<tr><td>1:30 a.m.</td><td>Prep buses for recording</td><td>Prep buses for recording</td></tr>
<tr><td>2:00 – 5:30 a.m.</td><td>Record XBL segments</td><td>Localize from previous day recording; record more segments if necessary</td></tr>
<tr><td>6:00 a.m.</td><td>Move buses to storage area</td><td>Move buses to storage area</td></tr>
<tr><td>6:30 a.m.</td><td>Copy data off computers</td><td>Copy data off computers</td></tr>
<tr><td>7:00 a.m. – 5:30 p.m.</td><td>Process map (automated process)</td><td>Process map (automated process)</td></tr>
<tr><td>6:00 p.m.</td><td rowspan="4">Draw lane map</td><td></td></tr>
<tr><td>6:30 p.m.</td><td>Move bus to training area</td></tr>
<tr><td>7:00 p.m.</td><td rowspan="3">Create driver training map</td></tr>
<tr><td>7:30 p.m.</td></tr>
<tr><td rowspan="2">8:00 – 9:30 p.m.
10:00 p.m.</td><td rowspan="2"></td></tr>
<tr><td>Move buses to storage area</td></tr>
</table>

Test Methodology and Results

System checkout, obstacle detection, deviation from mapped path to demonstrate automated lane keeping, headway to demonstrate CACC, automated merging, and speed to demonstrate passenger comfort and throughput testing were undertaken at the SwRI test track (off-site) and along the XBL (on-site).

System Checkout Test

The first test was a general system checkout. A complete route was driven autonomously with a manual takeover near the end of the route. One autonomous CAB and one manually driven CAB were present during the test to demonstrate vehicle connectivity. Control was demonstrated through the touchscreen UI. An error message displayed in the UI would depict failure, such as what the CAB operator would see should a loss of Ranger functionality (i.e., localization) occur.

Figure 4-4 *UI screenshot during Ranger loss*

Off-Site (SwRI Facility) System Checkout Test

The following 15 system checkout tests were successfully performed on each CAB:

1. CAB takeover with takeover button.
2. CAB takeover with accelerator input.
3. CAB takeover with brake input.
4. CAB takeover with steering input.
5. Visual/Audible UI feedback for loss of Ranger.
6. Visual/Audible UI feedback for loss of sensors.
7. Visual/Audible UI feedback for loss of CAN data.
8. UI displays object on the path.
9. UI displays gap policy and allows modification.

10. CAB is receiving data from connected CABs.
11. CAB brake lights illuminate when autonomously braking.
12. CAB can engage robotic mode in defined autonomous region when operator designates.
13. CAB alerts operator to take over at end of defined autonomous region.
14. CAB comes to stop at end of defined autonomous region if operator does not take over.
15. CAB can operate successfully at sunset/sunrise.

On-site (XBL) System Checkout Test

No on-site (XBL) system checkout test was conducted due to the need to prioritize the completion of other tests and data collection during the 12:30–5:30 a.m. period when the XBL was set up for the demonstration project.

Obstacle Detection Test

A demonstration with cones and other objects placed along a given route exhibited the autonomous CAB stopping for objects to prevent collisions.

Off-site (SwRI Facility) Obstacle Detection Test

The following three obstacle detection tests were successfully performed on each CAB at 15 mph:

1. CAB stops for large cone directly on vehicle path.
2. CAB ignores small cone directly on vehicle path.
3. CAB stops for Jersey barrier directly on vehicle path.

On-site (XBL) Obstacle Detection Test

No on-site (XBL) obstacle detection test was conducted due to the need to prioritize the completion of other tests and data collection during the 12:30–5:30 a.m. period when the XBL was set up for the demonstration project.

Automated Lane Keeping

CABs were tested to assess the viability of automated lane keeping. Automated lane keeping would address the project goal of preventing (or mitigating the effect of) incidents that negatively affect the reliability and effective capacity of XBL operations, and the objective of improving the efficiency of XBL operation by reducing the frequency of closures due to delineators being taken out of service and reset. The hypothesis is that automated lane keeping can offer a greater level of lateral control for the CAB operator.

Table 4-2 *Automated Lane Keeping Evaluation Approach and Criteria*

Metric	Measurement	Method of Measurement	Desired Outcome Evaluation
Delineators displaced	% of total displaced delineators	Manual counting	Desired: Zero displacements Test Metric: Maximum of 1% on straightway and 3% on curves during the POC
Lateral lane keeping (XBL straightaway)	% time bus is within 12, 9, 6, and 3 inches of the delineator or lane line	Black box measuring distance relative to mapped lane centerline	Desired: 100% within 6 inches of desired path Test Metric: 50% within 6 inches of desired path and 90% within 12 inches of desired path
Lateral lane keeping (Helix)	% time corners of the bus are within 12, 9, 6, and 3 inches of the delineator or lane line		Desired: 100% within 6 inches of desired path Test Metric: 40% within 6 inches of desired path and 80% within 12 inches of desired path
Frequency of disengagement / human intervention	Average # of disengagements per run	Manual counting	Desired: Zero disengagements Test Metric: No more than two on any run, average of less than one

SwRI's Ranger system was deployed on the CABs to monitor the roadway under the vehicles to identify their exact location based on previously mapped and stored roadway data. Data were collected to determine dynamic distances to the virtual lane line and to match the live ground imagery to imagery stored in the CAB's map.

Off-site (SwRI Facility) Automated Lane Keeping Test

The automated lane keeping test was performed on each CAB three times. During testing, it was observed that lateral movement of the vehicles while driving autonomously on the 35 mph section appeared greater than anticipated, due to vehicle tolerances that decline with age. As a result, CABs 2 and 3 were tested at lower speeds on that straightaway; CAB 1 was not included in this retest to maintain the schedule.

Test results are summarized in Tables 4-3 and 4-4. The Metric column describes the deviation amount (in inches) followed by the minimum path width of the CAB (assuming CAB width of 102 inches). The minimum path width is calculated by doubling the deviation and adding 102 inches to account for the CAB width.

Table 4-3 *CAB 1 Deviation from the Mapped Path at the SwRI Facility Test Track*

Deviation from Mapped Path		
Metric	XBL Travel Path	35 mph
Average deviation (inches)	(inches)	4.74
Percent of time within 3”	(9’0”)	42.84
Percent of time within 6”	(9’6”)	67.23
Percent of time within 9”	(10’0”)	87.20
Percent of time within 12”	10’6”	94.40
Percent of time within 15”	11’0”	97.21
Percent of time within 18”	11’6”	99.40
Percent of time within 21”	12’0”	99.82
Percent of time within 24”	12’6”	100.00

Table 4-4 *CABs 2 and 3 Deviation from Mapped Path at SwRI Facility Test Track*

Deviation from Mapped Path							
Metric	XBL Travel Path	35 mph		25 mph		15 mph	
		CAB 2	CAB 3	CAB 2	CAB 3	CAB 2	CAB 3
Average deviation (inches)	(inches)	6.06	8.24	6.07	6.67	4.63	5.89
Percent of time within 3”	(9’0”)	25.73	2.69	13.90	10.64	25.96	6.38
Percent of time within 6”	(9’6”)	58.95	40.34	49.45	42.14	80.89	60.41
Percent of time within 9”	(10’0”)	76.57	60.99	83.35	77.29	88.63	88.37
Percent of time within 12”	10’6”	91.45	83.16	100.00	97.92	98.94	98.66
Percent of time within 15”	11’0”	95.37	92.35	100.00	100.00	100.00	100.00
Percent of time within 18”	11’6”	98.16	98.3	100.00	100.00	100.00	100.00
Percent of time within 21”	12’0”	100.00	99.78	100.00	100.00	100.00	100.00
Percent of time within 24”	12’6”	100.00	100.00	100.00	100.00	100.00	100.00

The most critical component for a CAB successfully driving on the XBL is its ability to lane keep. This means the most important test is the deviation from mapped path testing. Considering that the bollards and Jersey barriers along the XBL have a minimum of 11′6″ spacing between them, the CABs appeared to operate at the border of success and failure.

CAB 2 appeared to move one of the Jersey barriers during a couple of its runs around the track at 35 mph, but when the speed was reduced to 25 mph and 15 mph, the mapped deviation was well within acceptable range. In the current state of the software and hardware, sections as narrow as 11′6″ should have an operational speed limit less than 35 mph for the CABs. It is possible to achieve improvement by adjusting steering control parameters. However, some deviations are due to the age of buses as well as performance issues that arose because of layers of steering and DBW components

On-site (XBL) Automated Lane Keeping Test

This test was performed on each CAB over the autonomous region of the XBL. One complete run was performed for speeds up to 25 mph and speeds up to 18 mph. Lower speeds were chosen because of the observed lateral movement of the CABs while driving autonomously at 35 mph during the off-site testing.

Test results are summarized in Table 4-5. The Metric column describes the deviation amount (in inches) followed by the minimum path width of the CAB (assuming CAB width of 102 inches). The minimum path width is calculated by doubling the deviation and adding 102 inches to account for the CAB width.

Table 4-5 *CABs 1, 2, and 3 Deviation from Mapped Path on the XBL*

Deviation from Mapped Path							
Metric	XBL Travel Path	25 mph			18 mph		
		CAB 1	CAB 2	CAB3	CAB 1	CAB 2	CAB 3
Average deviation (inches)	(inches)	3.99	9.68	5.57	2.90	8.34	3.98
Percent of time within 3”	(9’0”)	41.36	0.10	17.36	52.22	0.54	30.12
Percent of time within 6”	(9’6”)	78.47	14.02	60.22	95.30	22.13	88.42
Percent of time within 9”	(10’0”)	96.05	46.70	87.67	100.00	62.60	100.00
Percent of time within 12”	10’6”	98.83	78.22	99.18	100.00	92.01	100.00
Percent of time within 15”	11’0”	99.46	90.80	100.00	100.00	98.69	100.00
Percent of time within 18”	11’6”	100.00	96.95	100.00	100.00	99.05	100.00
Percent of time within 21”	12’0”	100.00	99.64	100.00	100.00	99.21	100.00
Percent of time within 24”	12’6”	100.00	100.00	100.00	100.00	99.34	3.98

The results above are similar at 25 mph for the off-site to on-site tests; however, at the lowest speed CAB 3 (and likely CAB 1) appears to improve. At first glance, it appears CAB 2 was not able to stay centered in the lane. CAB 2 drove 8–10 inches to the right of the center of the lane the entire time. After reviewing the data, the most likely cause of this was a poorly calibrated steering center. This can occur if the DBW does not catch a rollover event for the steering or if the steering calibration is no longer accurate. A steering calibration was performed for each CAB before testing on the XBL. It is not clear what caused any changes in the calibration, but CAB 2 was not able to command a straight curvature.

On-site testing also found that lighting reflectivity can be intense along sections of the XBL, particularly during nights when it rains. This resulted in consistent disengaging of the automatic lane keeping on a short section of the XBL on CAB 2. Highly reflective surfaces such as cars, signs, and the sides of the bus can exacerbate multipath and objects that are not in front of the vehicle can appear to be in front of the vehicle. This causes CABs to occasionally slow down for obstacles that are not there. Improvements to mitigate these impacts can be implemented as a part of the pilot program. There are some straightforward solutions that will prevent those false returns from propagating through the LiDAR pipeline; however, they were not able to be implemented in time for the remainder of the on-site testing.

A few delineators were "hit" by CAB 2 in the straightway section of the XBL on the Palisades, but not displaced. No other delineators were hit or displaced along the XBL when the CABs traveled 18 or 25 mph.

Cooperative Adaptive Cruise Control

CABs were tested to assess the viability of cooperative adaptive cruise control. CACC would address the project goal of demonstrating improvements to traffic flow and effective capacity of the XBL by maintaining closer following distances and consistent speeds over the 2.5-mile XBL. CACC could also meet the project objectives of improving the mobility of XBL operation by decreasing the 85th percentile headway to 4.5 seconds or less from the current 5.5 seconds and increasing the capacity from 650 buses per hour to 840 buses per hour. The hypothesis is that a proper following distance behind another bus can be achieved when buses cooperate by communicating with each other. The result is that buses will be able to follow one another more closely, accurately, and safely, with braking and accelerating done cooperatively and synchronously.

Table 4-6 *CACC Evaluation Approach and Criteria to Assess Throughput*

Evaluation Metric	Measurement	Method of Measurement	Desired Outcome
Average headway between two CABs	Time between buses (nearest 0.01 s)	Black box continuously recording location by time	Desired: 4.5 s Test Metric: Within 5.0 s
Average headway to a non-CAB	Time between buses (nearest 0.01 s)	Black box recording virtual paths as above	Desired: 4.5 s Test Metric: Less than existing 5.5 s headways
Reaction time to lead CAB, maximum braking	Time lag between brake applications (nearest 0.01 s)	Black box continuously recording brake use	Desired: 0.00 s Test Metric: Does not hit lead CAB
Reaction time to lead non-CAB, maximum braking	Distance to lead bus plotted by time	Black box recording location over time; proxy because lead bus will not have throttle data	Desired: 0.00 s Test Metric: Does not hit lead non-CAB
Reaction time and performance to lead CAB, 50% braking	Time lag between brake applications (nearest 0.01 s)	Black box continuously recording brake use	Desired: 0.00 s reaction, 50% braking Test Metric: Does not hit lead bus and does not apply maximum braking
Reaction time and performance to lead non-CAB, 50% braking	Distance to lead bus plotted by time	Black box recording location over time; proxy because lead bus will not have throttle data	Desired: 0.00 s reaction, 50% braking Test Metric: Does not hit lead bus and does not apply maximum braking

s = second(s)

CABs were also tested to assess how CACC could address the goal of reliability and the objective of improving travel time for the XBL customer by measuring the variability of XBL travel speed and headways. The hypothesis is that variability can be used by the PANYNJ, its stakeholders, and bus carriers to improve operations and as such, travel time reliability.

Table 4-7 *CACC Evaluation Approach and Criteria to Assess Reliability*

Evaluation Metric	Measurement	Method of Measurement	Desired Outcome
Variability in average headway between two CABs	Times between pairs of buses (nearest 0.01 s)	Black box continuously recording location by time	Desired: $\sigma = 0$ Test Metric: $\sigma \leq 0.5$ s
Variability in average headway to a non-CAB	Times between pairs of buses (nearest 0.01 s)	Black box recording virtual paths as above	Desired: $\sigma = 0$ Test Metric: $\sigma \leq 1.0$ s

s = second(s)

Assessing the performance of the CACC system required measuring accuracy and consistency longitudinally rather than laterally. A complete run-through on the designated autonomous section was performed using three CABs. The lead CAB was driven at a speed of 5–10 mph below the speed limit to force the other two following CABs to maintain a headway. The user interface allows three preset headways to be maintained: 2, 3, or 4 seconds. During the entirety of this test, 2 seconds was the selected headway for each CAB. Headway was measured from the front of each following CAB to the rear of the CAB directly in front of it. This test was repeated for non-connected automated buses (non-CABs) in the same configuration.

Off-site (SwRI Facility) CACC Test

The CACC test was performed on two CABs in the follower position and on one manually driven CAB in the leader position. Table 4-8 summarizes the results.

Table 4-8 *CACC Test Results on the SwRI Facility Test Track*

Metric (seconds)	Result		
	CAB Headway to Manually Driven CAB	CAB Headway to CAB	CAB Headway to Non-CAB
Average headway	2.13	2.13	5.49
Headway standard deviation	0.05	0.09	0.67
Max headway	2.35	2.39	7.79
Min headway	1.99	1.70	3.68
Braking response time	N/A	N/A	N/A

Headway testing between CABs appeared reliable and smooth. However, the same cannot be said for headway between a CAB and a non-CAB. This is because the LiDAR pipeline draws bounding boxes around objects. These bounding boxes are unstable, and their edges vacillate. Consequently, the CAB is unable to accurately measure headway and is caught in a never-ending acceleration/deceleration cycle. Radar tracking would improve the performance of ACC in situations where CABs are following non-CABs. This can be accomplished with LiDAR, but radar is a better and less expensive solution.

The design of this test did not test the braking response time of the system.

On-site (XBL) CACC Test

This test was performed on two CABs in the follower position and on one manually driven CAB in the leader position. CAB headway to non-CAB was not recorded since the off-site demo proved this method to maintain headway was not reliable. Table 4-9 summarizes the results.

Table 4-9 *CACC Test Results on the XBL*

Metric (seconds)	Result	
	CAB Headway to Manually Driven CAB	CAB Headway to CAB
Average headway	4.06	4.96
Headway standard deviation	1.88	2.98
Max headway	15.87	16.40
Min headway	1.40	0.85
Braking response time	0.30	4.59

Headway testing between CABs appeared reliable and smooth. However, the results were not as consistent as the off-site demonstration results due to slowdowns caused by obstacles in the LiDAR pipeline. The average headway should be about 2 seconds, but it is skewed higher because the maximum headway for both scenarios was more than 15 seconds. This maximum headway occurred because the CABs were braking for obstacles that were not there and slowing down. Headway maintenance was proven in the off-site demonstration; therefore, simply improving the LiDAR pipeline to reduce the occurrence of fake obstacles would reduce the headway.

Braking response time was tested in the headway configuration as well. The manually driven lead bus was driven about 5 mph while the two CABS platooned behind it and came to an abrupt stop. The CAB immediately behind the manually driven bus began braking 0.30 seconds after the lead vehicle began braking. It is difficult to be more precise than +/- 0.05 seconds since the data used to measure the response was only generated at a frequency of 10 hertz.

This test was not as useful for the rear CAB because it was already moving slightly slower than the lead vehicles at the time of braking and due to the slight gap in the platoon, it took longer before it needed to stop. For the rear CAB, this is not a true indication of braking response time, but rather a slight accordion effect in the platooning. It is exaggerated in this case because the vehicles were moving slowly during the test. This test only appears to be applicable for the second vehicle in the platoon, and the braking response time for the rear vehicle should be ignored. The results are included in the table for completeness.

Automated Merging

CABs were tested to assess the viability of automated merging. Automated merging would address the demonstration project's goal of preventing (or mitigating) the effect of deviations in traffic flow that negatively affect the reliability and effective capacity of XBL operations, and the objective to increase the productivity of buses entering the contraflow XBL at its western end (the teardrop) by improving bus merging. The hypothesis is that proper merging can be achieved when buses cooperate by communicating with each other. Buses will be able to merge more closely, accurately, and safely, with braking and accelerating done cooperatively and synchronously.

Table 4-10 *Automated Merging Evaluation Approach and Criteria*

Evaluation Metric	Measurement	Method of Measurement	Desired Outcome
Merge positioning	Merge point distance from end of lane	Black box measuring distance relative to other buses	*Desired:* Merge completed within 100 feet of where lanes meet *Test Metric*: Merge completed at least 50 feet from end of taper
Merge aggression	Time from reaching merge point to completing merge	Black box recording location over time	*Desired*: Bus merges smoothly without any buses coming to a complete stop *Test Metric*: Alternate merging is maintained; average headway between buses (downstream) is also a proxy metric
Average headway between two CABs at merge point	Time between buses (nearest 0.01 second)	Black box continuously recording location by time	*Desired*: 4.5 second-headways *Test Metric*: Same as downstream

Each CAB entering the XBL was manually driven from its origin. Once the CAB entered the XBL at the teardrop, the operator activated the ADS to engage lateral and longitudinal control. Operators had the option to override the ADS by turning the steering wheel, applying the brake, or applying throttle pressure. CAB operators were considered manual operators before they enabled the ADS, after they overrode the ADS, and after the ADS transitioned control back to the operator.

Once the ADS was active, the CABs adapted their speed and steering as necessary to optimize safety considering the other merging CABs and the available merge lane space. Lateral spacing, relative lateral velocity, uncertainty, and vehicle dynamic response capabilities all influenced the safety of the CAB.

Vehicle-to-vehicle wireless communications facilitated automated merging. The CABs in the teardrop adapted to the other merging CABs. A laterally encroaching

CAB demonstrated a physical response, as appropriate, both longitudinally and laterally when merging with the CABs. Lateral response was limited to the lateral constraints of the lanes and other objects.

A CAB already in the teardrop adjusted its own longitudinal position with throttle and braking when another CAB was merging. With steering actuation, CABs adapted to merging CABs using all actuators as needed to ensure safety considering the CABs around them. Safety considerations overrode other control priorities of the ADS.

All three CABs were autonomously operated in three configurations to verify merging was successful at the designated location. In the first configuration, the merging CAB waited to merge until two CABs with the right-of-way passed by. In the second configuration, the merging CAB merged in front of the other two CABs with the right-of-way. In the third configuration, the merging CAB merged between the two CABs with the right-of-way.

Off-site (SwRI Facility) Automated Merging Test

The speed limit in the merging region was set at 15 mph, which is identical to the teardrop merging location on the XBL. This test required the use of all three CABs. Table 4-11 summarizes each of the three automated merge scenarios and provides a headway analysis of the CABs while merging.

Table 4-11 *Automated Merging Test Results on the SwRI Facility Test Track*

Test Item	Result
Merging CAB merges in front of CABs when given enough room	Pass
Merging CAB merges in between two CABs when given enough room	Pass
Merging CAB merges behind CABs when it is not possible to merge in front or in between CABs	Pass
Metric (seconds)	**Result**
Minimum time between merging CAB and leading CAB during merge	4.03
Minimum time between rear CAB and merging CAB during merge	2.43

Automated merging worked in the three testable configurations. A notable observation is that the merging CAB allowed for more headway to the lead CAB than the rear CAB allowed for the merging CAB. It appears this is related to the curvature of the test track road at the merge point. The merging CAB slows down at the merge point to maintain a path along the test track. This slowdown was unexpected and not typical for the merge points on the XBL. The XBL teardrop has a smoother curvature at the merge point, as well as a longer merging region.

On-site (XBL) Automated Merging Test

The speed limit in the teardrop merging region was 15 mph. This test required the use of all three CABs. Table 4-12 summarizes each of the three merge scenarios and a headway analysis of the CABs while merging.

Table 4-12 *Automated Merging Test Results on the XBL*

Test Item	Result
Merging CAB merges in front of CABs when given enough room	Pass
Merging CAB merges in between two CABs when given enough room	Pass
Merging CAB merges behind CABs when it is not possible to merge in front or in between CABs	Pass
Metric (seconds)	**Result**
Minimum time between merging CAB and leading CAB during merge	1.79
Minimum time between rear CAB and merging CAB during merge	3.60

Merging worked in the three testable configurations. A notable observation is that in both off-site and on-site demonstrations slowdowns occurred at the merge point for different reasons. Slowdowns at the merge point for the XBL appear to be caused by adjustments for headway when following the lead CAB. This scenario was only encountered on the XBL as SwRI's test track did not allow for merging without slowdowns. Adding a transition from merging to the anticipated CACC mode along the mainline XBL should improve the performance and the consistency of the gap at the teardrop.

Speed Profile

CABs were tested to assess the project goal of demonstrating improvements to traffic flow and effective capacity of the XBL by sustaining consistent speeds over the 2.5-mile XBL. By coupling longitudinal and lateral CAB behavior and surrounding lane constraints, CACC will provide smooth acceleration and deceleration—and therefore passenger comfort—beyond what can be done with conventional camera and radar sensors used for adaptive cruise control. The CAB autonomy software controls both headway and vehicle speed. The autonomy software can be configured with acceleration/deceleration parameters tuned for passenger comfort. More aggressive braking will occur to prevent collisions in situations that require it. The following aspects of speed were collected:

- Speed of the vehicle
- Deviation from the posted speed limit
- Intensity of accelerations
- Intensity of decelerations

The deviation impacts XBL throughput, acceleration, deceleration, and passenger comfort.

Table 4-13 *CACC Evaluation Approach and Criteria*

Evaluation Metric	Measurement	Method of Measurement	Desired Outcome
Average speed	Distance/total time	Black box	Desired: 35 mph when demand is less than capacity Test Metric: 25 mph minimum average, demand less than capacity
Maximum speed	Recorded mph	Black Box recording speed over time	Desired: 35 mph (speed limit) Test Metric: 38 mph (3 mph tolerance)
Variability in average speed	Distance/total time for several runs	Black box measuring time over distance	Desired: Same speed for every bus on every run Test Metric: $\sigma \leq 5$ mph

Off-site (SwRI Facility) Speed Profile Test

The speed profile test was performed for each CAB. The results are summarized in Tables 4-14 and 4-15. Acceleration and deceleration data were collected from the CAB's Inertial Measurement Unit (IMU). IMUs are inherently noisy, so the data were passed through a moving average filter to remove the high frequency changes inherent to IMUs. The IMU deployed on each CAB produced data at 100 hertz, so the window size chosen was 100 to average the samples collected each second.

Table 4-14 *Passenger Comfort Test Results on the SwRI Facility Test Track*

Test Item	Result	Comments
Accelerations are comfortable for passengers	Pass	Sometimes the speed controller paired with transmission shifts causes undulation
Decelerations are comfortable for passengers	Pass	Late detection of obstacles can cause abrupt braking

Table 4-15 *CABs 1, 2, and 3 Speed Profile Test Results on the SwRI Facility Test Track*

Metric	Result		
	CAB 1	CAB 2	CAB 3
Average speed deviation from setpoint (mph)	0.69	1.49	0.72
Speed deviations from setpoint standard deviation (mph)	0.89	2.46	0.94
Maximum speed deviation from setpoint (mph)	3.67	25.32	3.66
Maximum speed (mph)	33.89	33.93	34.02
Minimum speed (mph)	0.00	2.88	0.00
Maximum acceleration (mph/second)	4.02	2.72	2.51
Maximum deceleration (mph/second)	-2.78	-9.52	-3.02

From a passenger comfort perspective, the speed profile testing went well. Planned accelerations, turns, and decelerations were smooth. CAB 2 experienced some slight undulation when it was shifting gears, but the undulations went away as CAB 2 maintained consistent speed. Sudden decelerations occurred when objects appeared in the route, but the decelerations were not too aggressive for passenger comfort. CAB 2 had trouble with the bollards and Jersey barrier section. CAB 2's LiDAR was slightly out of alignment and the barriers appeared to be in the path. Therefore, CAB 2 appeared to have high speed deviations. CAB 2's speed controller was commanded to stop in an instant because an object was seen directly on the path, which caused a large speed deviation for a moment. The other CABs did not stop for objects during the speed profile runs, so large deviations were not observed.

On-site (XBL) Speed Profile Test

The speed profile test was performed for each CAB. The results are summarized in Tables 4-16 and 4-17. Acceleration and deceleration data were collected from the CAB's IMU and averaged in the same manner as the off-site speed profile test.

Table 4-16 *Passenger Comfort Test Results on the XBL*

Test Item	Result	Comments
Accelerations are comfortable for passengers	Pass	Sometimes the speed controller paired with transmission shifts causes undulation
Decelerations are comfortable for passengers	Pass	Late detection of obstacles can cause abrupt braking

Table 4-17 *CABs 1, 2, and 3 Speed Profile Test Results on the XBL*

Metric	Result		
	CAB 1	CAB 2	CAB 3
Average speed deviation from setpoint (mph)	0.87	0.97	0.87
Speed deviations from setpoint standard deviation (mph)	0.88	1.13	0.88
Maximum speed deviation from setpoint (mph)	15.63	15.12	15.63
Maximum speed (mph)	25.30	25.31	25.30
Minimum speed (mph)	0.57	0.01	0.57
Maximum acceleration (mph/second)	3.71	2.63	3.71
Maximum deceleration (mph/second)	-3.69	-5.36	-3.69

From a passenger comfort perspective, the speed profile testing went well. Planned accelerations, turns, and decelerations were smooth.

Similar to the off-site testing, CAB 2 experienced some slight undulation when it was shifting gears, but the undulations went away as CAB 2 maintained consistent speed. Sudden decelerations occurred when objects appeared in the route, but the decelerations were not too aggressive for passenger comfort. They were only uncomfortable in the sense that the braking was unexpected because there were no obstacles in front of the bus.

Each CAB experienced issues at points along the XBL where objects appeared seemingly out of nowhere to the CAB. In an instant, the CAB was commanded to slow down or stop for an obstacle before the obstacle disappeared for the CAB. Therefore, the maximum speed deviations are high. It takes some time for the CAB to slow down to the commanded speed. Real obstacles are generally observed at a distance so this speed deviation would not be as great. The cause of this was determined to be that LiDAR returns were being reflected off the side of the bus and other highly reflective surfaces (e.g., cars or road signs). Due to the multipath issue, these LiDAR returns appeared to be coming from directly in front of the bus, which caused the sudden braking. This behavior was not observed at the off-site demo at SwRI's test track.

CAB Operator Feedback

CAB operators were interviewed to assess the project's goal of adopting CAB technologies that would enhance the safety, reliability, and effective capacity of the XBL, and the objective of improving traffic safety on the XBL with a goal of zero collisions through CAB technologies. The strategy was to obtain CAB operator feedback. The hypothesis is that SAE Level 3 vehicles contain the lowest-tier system that is classified as an automated driving system as opposed to a manual system. With this more advanced technology, L3 vehicles can make informed decisions for themselves; however, human override is required when the machine is unable to execute the task at hand or the system fails.

A qualitative assessment was undertaken to determine the CAB operator's response to an overall perception of the technology's effectiveness (i.e., extremely, very, moderately, slightly, and/or not effective) in the areas of manual and automated initiation and disengagement of L3 braking, steering and throttle, ease of use, understanding the information presented to them, whether L3 autonomy is helpful in general, and risk.

Table 4-18 *CAB Operator Evaluation Approach, Criteria, and Results*

Evaluation Metric	Measurement	Method of Measurement	Desired Outcome	CAB Operator Average Rating
Operator response to initiating L3 braking autonomy	Qualitative assessment rated as follows: (1) extremely effective, (2) very effective, (3) moderately effective, (4) slightly effective, and (5) not effective	CAB operator interview	Information that can be used to establish desired future goals with bus carriers	1.0
Operator response to initiating L3 steering autonomy				1.0
Operator response to initiating L3 throttle autonomy				1.0
Operator response to initiating disengagement of L3 braking autonomy				1.5
Operator response to initiating disengagement of L3 steering autonomy				1.5
Operator response to initiating disengagement of L3 throttle autonomy				1.5
Operator response to automated initiation of L3 braking				1.5
Operator response to automated initiation of L3 steering				2.5
Operator response to automated initiation of L3 throttle				1.5
Overall operator perceptions of L3 braking autonomy				3.0
Overall operator perceptions of L3 steering autonomy				3.0
Overall operator perceptions of L3 throttle autonomy[1]				2.0
Operator thoughts on ease of use				1.5
Operator thoughts on ease of understanding the information provided to the operator[2]				1.5

[1] *CAB operators noted that the automated system was very responsive; however, it was still very peppy on the throttle and the throttle could use some improvement.*

[2] *CAB operators noted that once they were shown how to use the UI that it was easy to understand.*

Table 4-18 (cont.) *CAB Operator Evaluation Approach, Criteria, and Results*

Evaluation Metric	Measurement	Method of Measurement	Desired Outcome	CAB Operator Average Rating
Operator thoughts on whether L3 autonomy contributes to operator safety[3]	Qualitative assessment rated as follows: (1) extremely effective, (2) very effective, (3) moderately effective, (4) slightly effective, and (5) not effective	CAB operator interview	Information that can be used to establish desired future goals with bus carriers	3.5
Operator thoughts on whether L3 autonomy contributes to overall safety[4]				4.0
Operator thoughts on whether L3 autonomy is helpful to the operator[5]				4.0
Operator thoughts on whether L3 autonomy is helpful in general[6]				4.5
Operator thoughts on distractions[7]				1.0
Does the operator want L3 autonomy in the bus[8]				5.0
Operator thoughts on actual risks[9]				5.0

[3] *CAB operators noted that the demonstration project is a work in progress and believe it will get better over time. Issues related to "sway" at speeds in excess of 20 mph where the CAB would swerve from side to side were noted. One operator noted they enjoyed the experience and would love to do it again when ready.*

[4] *CAB operators noted that ADS was far from being complete. It was noted that the CAB's operation was a little rough at times pertaining to jerking the wheel and braking hard.*

[5] *CAB operators noted that ADS is not there yet but believe ADS can be helpful in time.*

[6] *CAB operators noted that the CABs needed more testing and adjustments.*

[7] *CAB operators noted that ADS and UI were not a distraction at all. You simply engage it and let it go.*

[8] *CAB operators noted that ADS is not ready for prime time and the overall approach to calibration needs improvement.*

Simulation Modeling

While data were collected and evaluated from the field, simulation modeling was also undertaken to assess support for the following goals and long-term objectives of the demonstration project.

Table 4-19 *Simulation Modeling Goals and Objectives*

Goals	Demonstrate improvements to traffic flow and effective capacity of the XBL by sustaining closer following distances and consistent speeds over the 2.5-mile XBL
	Show the benefits of adopting CAB technologies to help prevent (or mitigate the effect of) incidents and deviations in traffic flow on the corridor, which negatively affect the reliability and effective capacity of XBL operation
Long-term Objectives	Improve traffic safety on the XBL with a goal of zero collisions through CAB technologies
	Reduce emissions and improve fuel efficiency due to reduced incidents and stop-and-go traffic

Simulation modeling was undertaken to compare CAB and passenger throughput, average headways, delay and fuel savings, emission reductions, and crash reductions between the 2016 existing peak hour throughout of 650 buses per hour and the 2040 future demand of 840 buses per hour over five levels of market penetration: 0%, 25%, 50%, 75%, and 100%. The AIMSUM model was used, which has an embedded module to simulate CACC. The module was adapted to use the demonstration project logic as input to the model. The current relative bus splits for the three XBL approaches—25% for NJ Route 3, 50% for the northbound NJ Turnpike, and 25% for the southbound NJ Turnpike—were maintained for the 2040 future demand. Simulation modeling results are summarized in Table 4-20 and Figure 4-5.

Table 4-20 *Potential CAB and Passenger Throughput and Average Headways*

		XBL Throughput (buses)	Passengers	Average Headways (seconds)
	Existing Observed Capacity (2016)	650	20,150	5.5
Proof of Concept Simulation Modeled at 2-Second Gap, 2040 Forecast Demand	25% – ADAS Equipped Buses	715	22,165	5.0
	50% – ADAS Equipped Buses	745	23,095	4.8
	75% – ADAS Equipped Buses	775	24,025	4.6
	100% – ADAS Equipped Buses	815	25,265	4.4
	2040 Forecast Demand	840	26,040	

ADAS = Advanced Driver Assistance Systems
Headway = Front of the lead bus to front of the following bus
Gap = Back of the lead bus to front of the following bus
Passengers = 31 passengers per bus for NJT weekday departures, October 2022

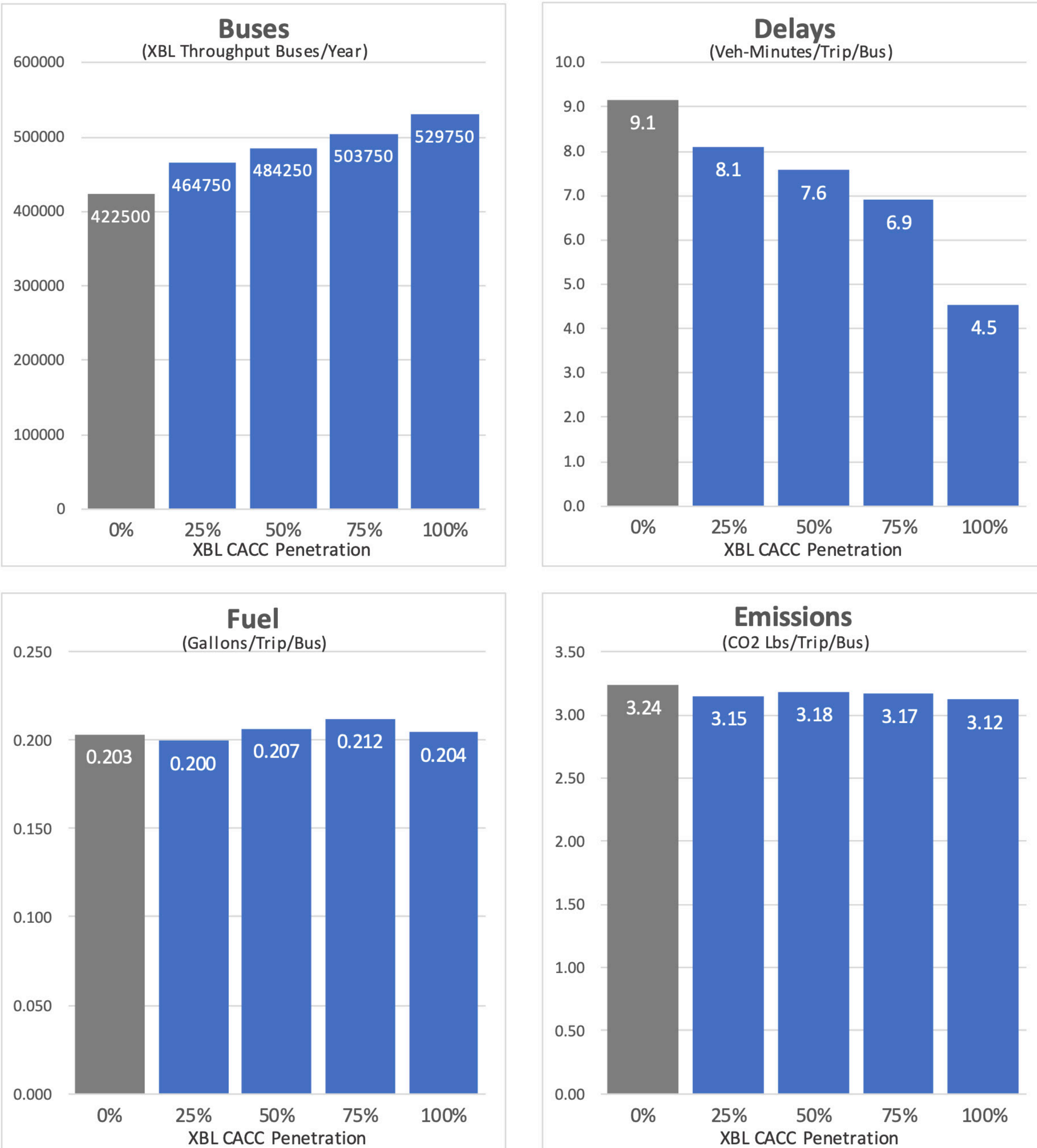


Figure 4-5 *Average XBL analysis results*

Section 5

Challenges and Accomplishments

A few challenges were anticipated in completing the XBL CAB Demonstration project. Chief among them were the safety concerns associated with retrofitting decommissioned MCI Coach D-45 buses and the uncertainty of the current technology's capability to meet the project goals. These were largely overcome; however, other unforeseen obstacles and challenges arose.

Challenges

COVID

The concept of operations, system requirements, and evaluation criteria were completed in 2019, which enabled PANYNJ to offer an Invitation to Bid to two vendors to outfit six MCI D45 Series buses for the demonstration project. Bids were received in July 2019, reviewed, and negotiations completed with two vendors in the first quarter of 2020. In March 2020, day-to-day business functions and operations of PANYNJ's 18 facilities ceased due to COVID. Everything went on hold. Once efforts restarted, supply chain issues negatively affected transport of the buses and procurement of parts.

Staff Turnover

Key staff turnover at both PANYNJ and SwRI impacted the project.

Local Funding

COVID resulted in a $3B loss of revenue for PANYNJ. This reduced the amount of available funding for the XBL CAB POC Demonstration project. As such, the PANYNJ selected one and not two vendors to undertake and complete the project.

Accomplishments

The demonstration project successfully tested and demonstrated effective technology solutions to enhance the safety, reliability, and effective capacity of the XBL. The project retrofitted three older NJ TRANSIT MCI Coach D-45 buses, deployed them on the XBL, and found they were able to safely merge, maintain headway, and keep within the lane, all while allowing the operator to switch between ADS and manual modes as needed.

Table 5-1 *ADS Meets XBL POC Demonstration Project Goals and Objectives*

Goal	CAB ADS Components
Demonstrate improvements to traffic flow and effective capacity of the XBL by sustaining closer following distances and consistent speeds over the 2.5-mile XBL	• CACC • Automated Merging
Show the benefits of adopting CAB technologies to help prevent (or mitigate the effect of) incidents and deviations in traffic flow on the corridor, which negatively affect the reliability and effective capacity of XBL operation	• Automated Lane Keeping • CACC • Automated Merging
Plan for the scaled adoption and deployment of effective technology solutions to enhance the safety, reliability, and effective capacity of the XBL	• Automated Lane Keeping • CACC • Automated Merging
Long-term Objective	**CAB ADS Components**
Improve travel time reliability by reducing average peak hour delay by 10 minutes due to reduced incidents and breakdowns and increased throughput on the XBL	• Automated Lane Keeping • CACC
Decrease headway to 4.5 seconds or less to support an increase in XBL throughput by 30% from the current 650 buses/hour to 840 buses/hour, effectively adding 10,000 peak-hour passengers to the 32,500 currently served	• CACC
Eliminate delineator strikes in the contraflow XBL, thereby reducing the frequency of XBL closures due to delineators being taken out of service and having to be reset	• Automated Lane Keeping
Increase the productivity of buses entering the contraflow XBL at its western end (the teardrop) by improving bus merging	• Automated Merging
Improve traffic safety on the XBL with a goal of zero collisions through CAB technologies	• Automated Lane Keeping • CACC • Automated Merging
Reduce emissions and improve fuel efficiency due to reduced incidents and stop-and-go traffic	• CACC • Automated Merging

Section 6

Lessons Learned and Next Steps

While the demonstration project was a success, there are lessons to be learned and conclusions that can be shared with others in the transit industry who might be looking to retrofit buses to provide ADS.

Lessons Learned

Refining Obstacle Detection

Further refinement is required if the CABs are to try to stop for small objects while traveling on the XBL. Small cones have undefined behaviors due to their short height. The LiDAR pipeline makes assumptions about low objects to approximate the ground plane. All CABs are anticipated to slow down when small cones are detected, but not all CABs will come to a stop in time for them. Due to their size, LiDAR detects them as objects too late to reliably stop for small cones. More stopping distance is required at higher speeds, and the smaller the object the lower the speed required to stop in time.

Refining Automated Lane Keeping

Testing data confirms that automated lane keeping is possible on the XBL, but it also suggests that further refinement of the control system is desired on the retrofit buses. A new DBW design and newer buses would likely overcome this issue, but alternate steering control strategies can also provide improvements. The demonstration project system design implemented on the three retrofit buses relies on a pure pursuit control algorithm. One known limitation of pure pursuit is that it requires a well calibrated steering system, and it is difficult to adequately calibrate the steering on these buses. It appears that pure pursuit is adequate but far from ideal for this task on these buses.

Calibration Takes Time

Ranger requires a preliminary data collection event along with automated map generation, optimization, and manual map refinement. This data collection can be performed by one of the automated vehicles or by an auxiliary vehicle outfitted with a temporary Ranger system; no expensive, additional mapping system is necessary. In addition, a single map can be shared among all the CABs without modification. This sharing means that any updates or changes to the map can also be quickly and easily shared with all CABs. However, a map is required.

Proper calibration in a complex environment like the XBL takes time, requiring multiple reruns. Retrofitted buses also perform differently from one another, and each will require its own calibration.

Reflectivity Can Present Challenges to ADS

A significant issue was discovered during the on-site demonstration regarding Ranger's performance. Ranger struggled to perform during light rain on certain sections of pavement, which caused the CABs to occasionally slow down for obstacles that were not physically present. Ranger has been proven to work in wet conditions as long as 30% of the road is visible; however, that was not the case at times during the on-site demonstration. Specular reflection can drown at the center of the Ranger image and prevent many features from being extracted. It appears to be related to the lighting configuration chosen for this Ranger installation. A lighting study that would recreate and demonstrate the cause of the matching issues could be undertaken to identify and implement a solution.

Know the Limitations of the Selected Technology

Ranger is not robust to complete occlusion or replacement of the road surface. A road surface completely covered in snow, for example, will disable Ranger. The same is true if a road surface is completely repaved or replaced, although a simple additional data collection run will resolve the issue in that case.

When the road surface is occluded, such as by snow, SwRI's CAB system will maintain operation for a configurable period of time. SwRI's custom state estimator can use other sensing modalities to provide high- quality driving for tens or hundreds of meters between Ranger updates; as a result, temporary occlusions, such as a few longitudinal meters of snow, will not affect system operation. To ensure both maximum safety and operator trust of the system, the operator can choose (at startup) the duration between updates, after which the system will consider itself to have failed and safely come to a stop.

Spend Time to Calibrate ADS in the Operational Design Domain

It is difficult to replicate the operational design domain on an off-site test track. While the intent is there, an exact replication is not possible. As such, additional time and effort is needed to properly calibrate a retrofitted CAB to the operational design domain prior to testing or deploying in revenue service.

The Age of the Bus Matters

Three, roughly 20-year-old NJ TRANSIT MCI D-45 Series commuter buses were retrofitted with the requisite hardware and software systems to enable DBW as well as ADS. There is "slop" in the multitude of parts, gearing, transmission, and torque lag associated with older combustion engine vehicles. In an ideal case, better control, more accurate response, and instant torque (no lag) would be seen with an electric bus, but the cost of an electric bus in the current marketplace is far more expensive than retrofitting a bus.

Next Steps

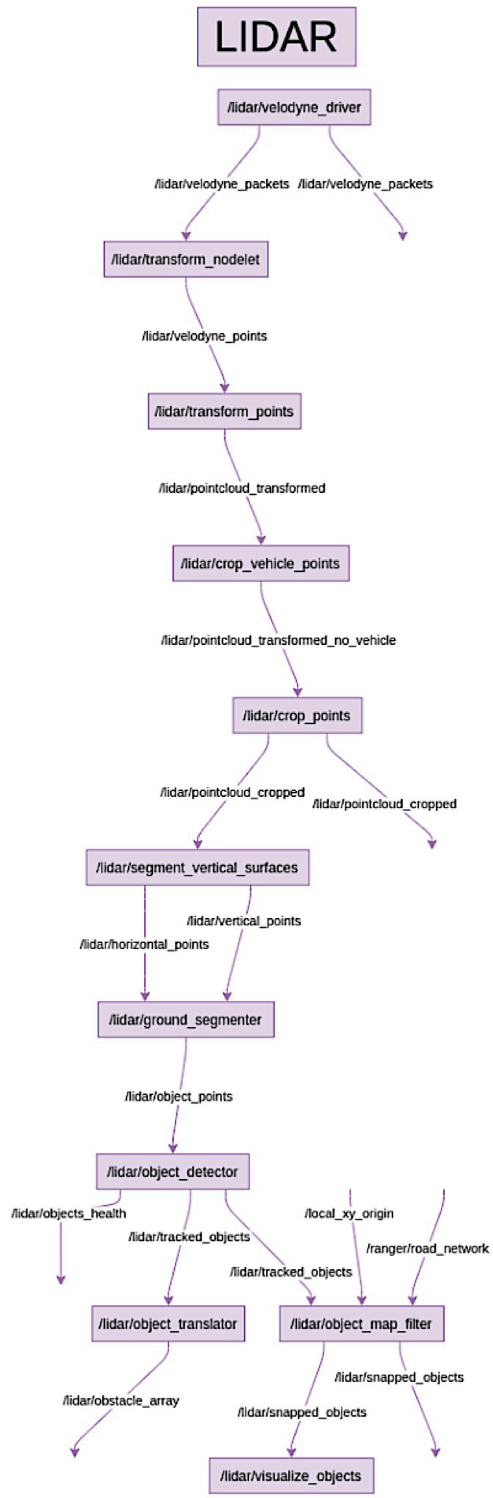
PANYNJ will work with stakeholder partners NJ TRANSIT and NJDOT in establishing a working group. The working group will be comprised of subject matter experts from each respective agency and focus on the following items:

- Determine desired technology applications
- Align with fleet life cycles and new procurements
- Evaluate optimal deployment scenario
- Investigate funding opportunities
- Develop plan for a scaled pilot deployment
- Determine regulatory and statutory considerations

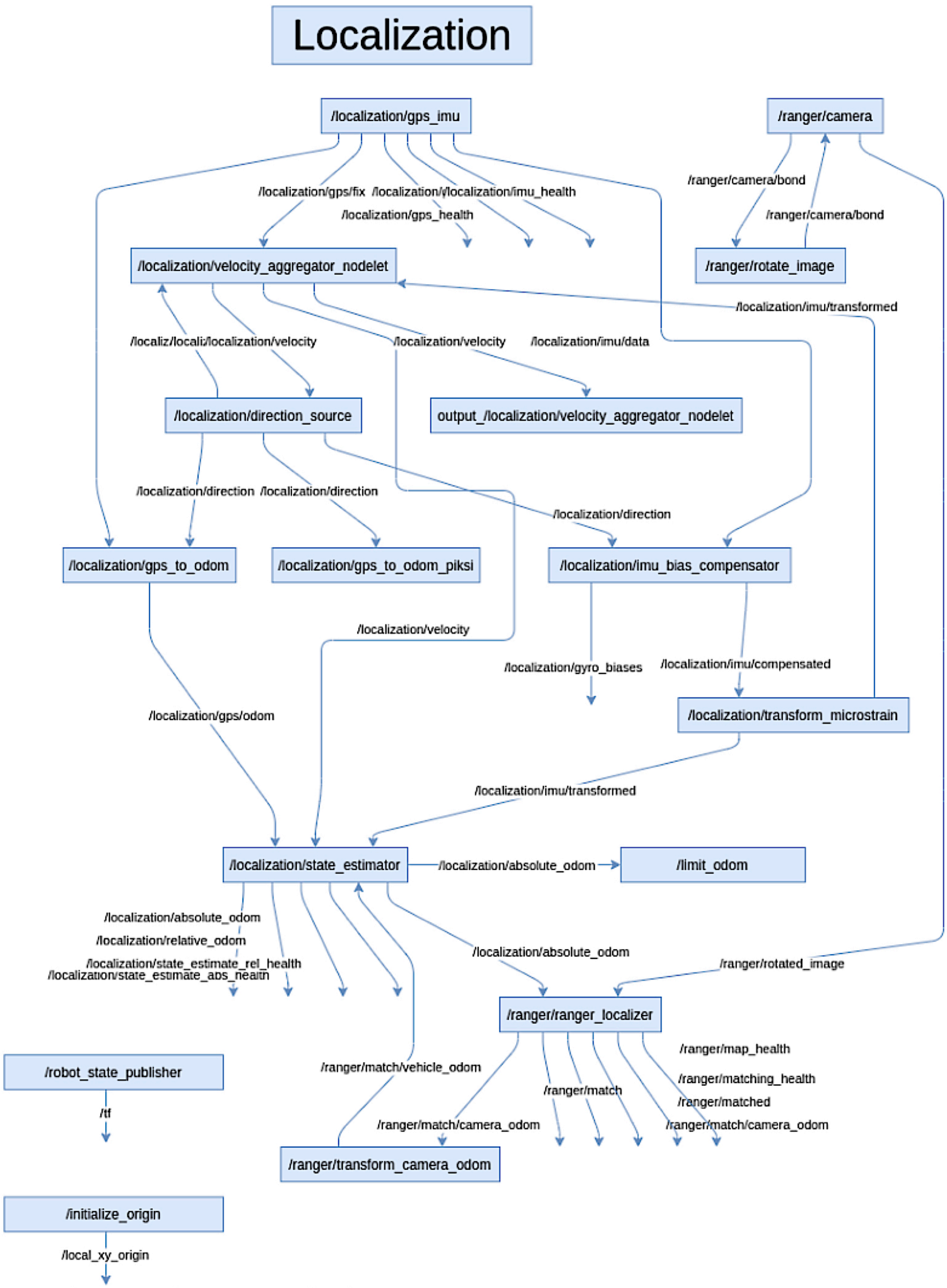
Acronyms and Abbreviations

ABW	Accelerator-by-wire
ACC	Adaptive cruise control
ADS	Automated Driving System
BBW	Brake-by-wire
CAB	Connected automated bus
CACC	Cooperative Adaptive Cruise Control
CAN	Controller Area Network
DBW	Drive-by-wire
DSRC	Dedicated short-range communications
FTA	Federal Transit Administration
GPS	Global Positioning System
IMU	Inertial Measurement Unit
L3	Level 3
LiDAR	Light Detection and Ranging
MBT	Midtown Bus Terminal
MCI	Motor Coach Industries
mph	Miles per hour
NJ	New Jersey
NJDOT	New Jersey Department of Transportation
NJTA	New Jersey Turnpike Authority
NJ TRANSIT	New Jersey Transit Corporation
PANYNJ	Port Authority of New York and New Jersey
POC	Proof of concept
ROS	Robot Operating System
SAE	Society of Automotive Engineers
SBW	Steer-by-wire
SwRI	Southwest Research Institute
UI	User interface
Veh	Vehicle
V2V	Vehicle-to-vehicle
XBL	Exclusive bus lane

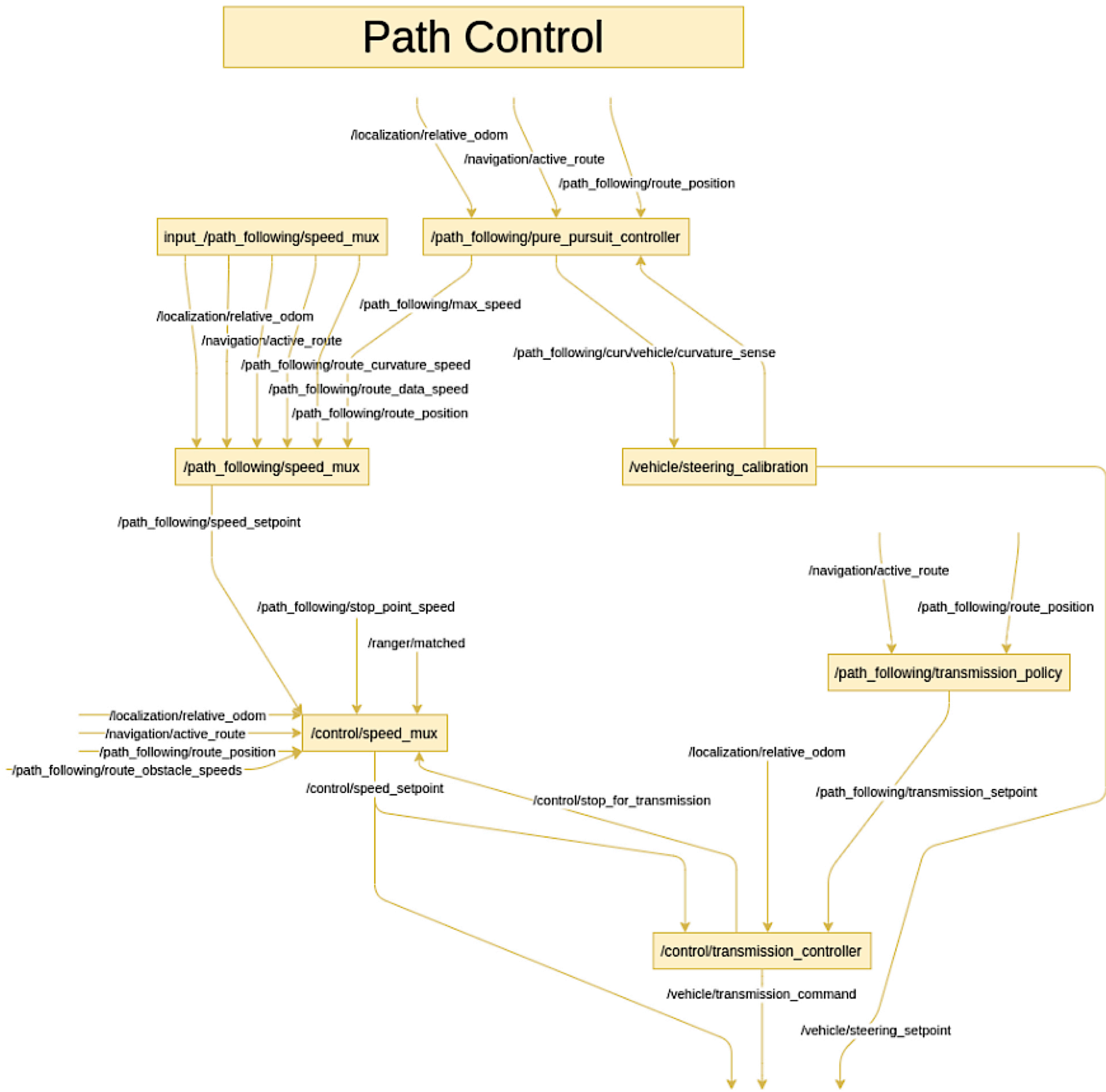
Appendix A Software Architecture Diagrams



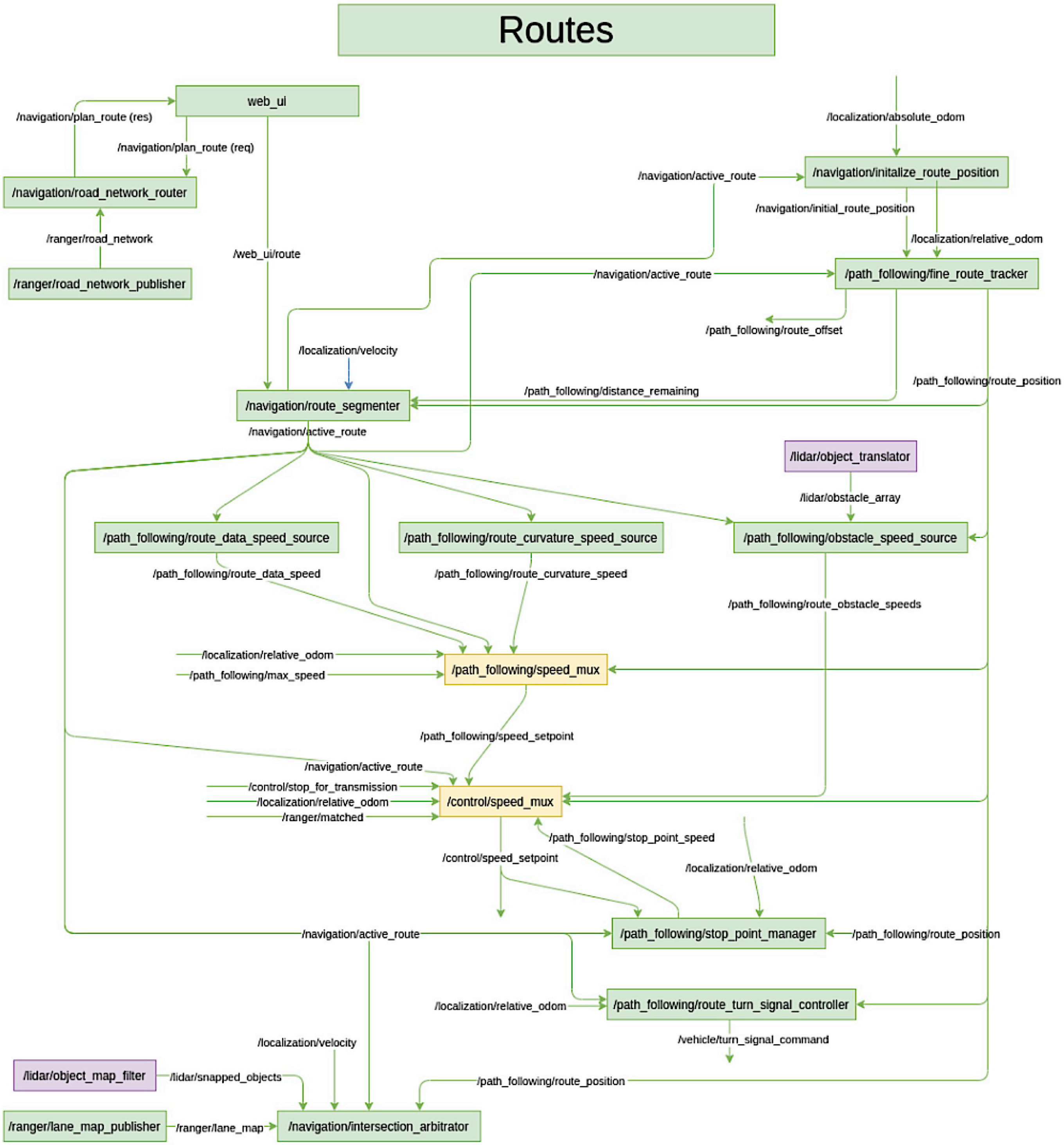
Software Architecture Diagram – Perception / LiDAR



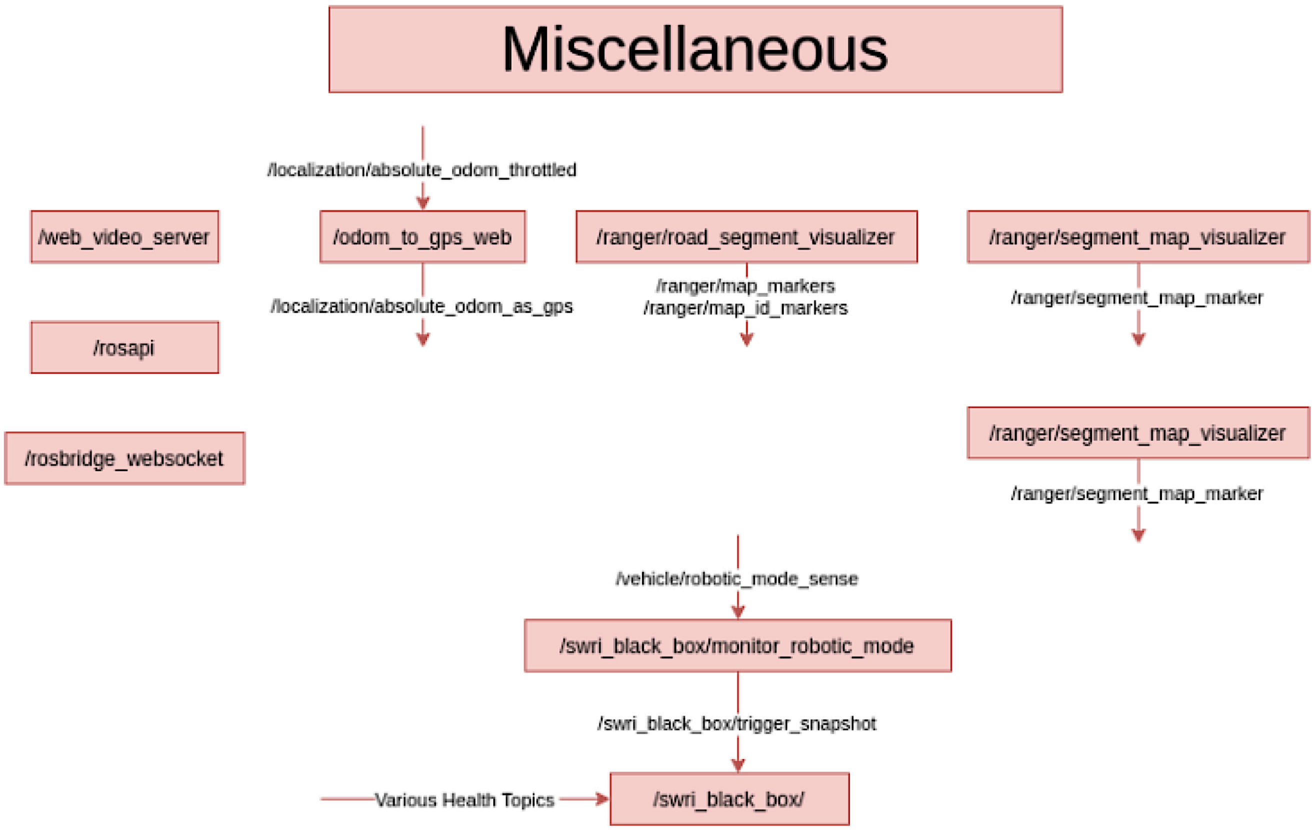
Software Architecture – Localization



Software Architecture – Navigation / Path Control



Software Architecture – Navigation / Routing



Software Architecture – Miscellaneous

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