FTA RESEARCH

FEDERAL TRANSIT ADMINISTRATION

Vehicle Assist and Automation Demonstration Report

AUGUST 2017

FTA Report No. 0113
Federal Transit Administration

PREPARED BY

California Department of Transportation (Caltrans)
Partners for Advanced Transportation Technology (PATH)

U.S. Department of Transportation
Federal Transit Administration

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California Department of Transportation (Caltrans)
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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	liter	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)				
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C

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13. ABSTRACT Vehicle Assist and Automation (VAA) systems enable lane-keeping and precision docking of transit vehicles. They offer the opportunities of providing high-quality transit service within reduced lane widths. Sponsored by the United States Department of Transportation, this VAA project aimed to demonstrate the technical merits and feasibility of VAA applications in bus revenue service. The VAA Demonstration project was carried out through the four phases of design, development, deployment, and operational tests. In the design phase, the system architecture and requirements were finalized, and test plans were generated for four levels of testing. All hardware and software components were developed in the development phase, and a 60-ft articulated bus was instrumented. In the deployment phase, system performance and reliability testing were conducted first at a test track and then on an operational route in Eugene, Oregon. After operational testing without passengers, revenue service at Lane Transit District commenced. Data from revenue service operations showed that the VAA system met its performance goals, specifically that lateral deviation was substantially smaller under automated operations than it was under manual driving.			
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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACRONYMS AND ABBREVIATIONS

AC	Transit Alameda–Contra Costa Transit District
ADA	Americans with Disabilities Act
BRT	Bus Rapid Transit
Caltrans	California Department of Transportation
CAN	Controller Area Network
CPHS	Committee for Protection of Human Subjects
CNG	Compressed Natural Gas
CUTR	Center for Urban Transportation Research
DGPS/INS	Differential Global Positioning System/Inertial Navigation System
ECM	Electronic Control Modules
FOT	Field Operational Test
FTA	Federal Transit Administration
GPS	Global Positioning System
HMI	Human-Machine Interface
HOV	High-Occupancy Vehicle
INS	Inertial Navigation System
ITS	Intelligent Transportation Systems
JPO	Joint Program Office
LTD	Lane Transit District
LED	Light-emitting diode
NBRTI	National Bus Rapid Transit Institute
PATH	Partners for Advanced Transportation Technology
RFS	Richmond Field Station
ROW	Right-of-way
SAE	Society of Automotive Engineers
UC	University of California
VAA	Vehicle Assist and Automation
VAA-PD	Vehicle Assist and Automation-Precision Docking
VAA-VG	Vehicle Assist and Automation-Vehicle Guidance
VAA-P	Vehicle Assist and Automation-Platooning
VAA-AVO	Vehicle Assist and Automation-Automated Vehicle Operation

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The VAA system would not be ready for deployment if it were not for the conviction and ardent support from the participating transit agencies. The PATH team could always rely on the LTD maintenance team led by George Trauger, Ernie Turner, and Don Swearingen for its expertise in bus components, installation, and maintenance as well as for testing coordination. Also, LTD instructors Marcus Hecker and Bill Mullican believed in this project and stayed countless hours during testing, sharing their insights and providing feedback.

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ABSTRACT

Vehicle Assist and Automation (VAA) systems enable lane-keeping and precision docking of transit vehicles. They offer the opportunities of providing high-quality transit service within reduced lane widths. Sponsored by the United States Department of Transportation, this VAA project aimed to demonstrate the technical merits and feasibility of VAA applications in bus revenue service. The VAA Demonstration project was carried out through the four phases of design, development, deployment, and operational tests. In the design phase, the system architecture and requirements were finalized, and test plans were generated for four levels of testing. All hardware and software components were developed in the development phase, and a 60-ft articulated bus was instrumented. In the deployment phase, system performance and reliability testing were conducted first at a test track and then on an operational route in Eugene, Oregon. After operational testing without passengers, revenue service at Lane Transit District commenced. Data from revenue service operations showed that the VAA system met its performance goals, specifically that lateral deviation was substantially smaller under automated operations than it was under manual driving.

EXECUTIVE SUMMARY

Vehicle Assist and Automation (VAA) systems offer the opportunity of providing high-quality transit service within reduced lane widths. They can provide four functions for buses: precision docking at bus stations, vehicle guidance or automatic steering on the running way between stations, automatic platooning at close separations, and fully-automated vehicle operations. The precision docking function facilitates passengers boarding and alighting at stations by enabling consistent positioning of the bus at stops, and vehicle guidance or automatic steering allows the bus to operate safely in a designated lane that is slightly wider than the bus itself. The systems can be implemented in partially- or fully-automated modes to guide buses through narrow bridges, tunnels, toll booths, and roadways, as well as bus stops, tight curves, and designated trajectories in maintenance yards. Transit operators are very interested in VAA for delivering rail-like service—an attractive feature to riders—at a fraction of the cost of rail.

To address the needs of the transit industry, the U.S. Department of Transportation (USDOT), through the Federal Transit Administration (FTA) and the Intelligent Transportation Systems Joint Program Office (ITS JPO), have spearheaded efforts in developing and demonstrating VAA systems as well as in assessing their impacts on bus-based transit systems. FTA is specifically interested in demonstrating two viable VAA applications that have been identified in recent research as having the most potential—precision docking and lateral guidance. These are core applications that VAA systems could enable in different transit operational scenarios.

Sponsored by FTA and ITS JPO, this VAA project aimed to demonstrate the technical merits and feasibility of different VAA technology applications in bus revenue service and to assess their costs and benefits. To achieve this goal, Caltrans partnered with Alameda–Contra Costa Transit District (AC Transit), Lane Transit District (LTD), the University of California Partners for Advanced Transportation Technology (PATH), and several private sector companies (through PATH). The project planned to include two VAA applications: bus lateral guidance (also referred to as lateral control, and lane-keeping) on an HOV lane and through a toll plaza, and lateral guidance on a bus rapid transit (BRT) busway and precision docking at BRT stops. These applications planned to use the two VAA sensing technologies: 1) magnetic marker sensing and 2) Differential Global Positioning System (DGPS) with inertial navigation system (INS).[1]

This VAA project was carried out through the four phases of design, development, deployment, and operations. In the design phase, the system architecture and requirements were finalized, detailed specifications for components and interfaces were developed, and the preliminary test and operational plans were generated. The development phase included the design, fabrication, and initial testing of all hardware and software components. The instrumentation of the first bus (for LTD) was also completed within the

[1]The LTD deployment tested the magnetic marker sensing technology only. The AC Transit deployment intended to test both sensing technologies, each as a primary source and the other as a backup; however, the project ended before the AC Transit applications became operational.

development phase. The deployment phase had two parallel efforts: conducting the performance and reliability testing using the first bus, and the instrumentation of the additional buses (AC Transit) based on the lessons learned from the first bus installation and initial testing. The operations phase involved the finalization of the operational plan, operational tests, data collection and analysis, feedback and operation modifications, and revenue operations as well as final documentation.

The VAA system design phase started with the development of the system requirements and interface requirements. System requirements include system performance specifications and technical specifications. Collectively, these specifications define the operational conditions and environments and specify the performance, reliability, safety, and maintainability of the system.

The general requirements for electronic guidance systems were revisited and used as a guideline in the design of the VAA system architecture and the development of the VAA system requirements. Based on these general requirements, the operational scenarios, the needs and performance requirements of the transit agencies, the past experience of the technical partners (including PATH and subcontractors of this project), and consultation with the transit agencies and project partners, the detailed system requirements were then determined and developed. Accordingly, detailed technical specifications were defined for each individual subsystem.

The resultant system requirements include the safety requirements, the performance requirements for individual functions, and the technical specifications for subsystems. The safety requirements include hardware redundancy and requirements for fault detection and management. The performance requirements specify the requirements for precision docking, lane-keeping, passenger ride quality, and human-machine interface (HMI) and driver interaction. The technical specifications include specifications for vehicle position sensing subsystem, vehicle status sensing subsystem, steering actuator, and HMI system, as well as requirements for infrastructure, driver qualification and training, and the maintenance interval.

The interface requirements specify the requirements on power supply, mechanical installation, and message formats for exchange on the data bus. Since the VAA system was designed as a retrofit or add-on system that would be connected to existing bus subsystems, it is important to understand how the VAA system can interface seamlessly with the two types of transit buses chosen for the VAA applications—a 60-ft articulated New Flyer bus and a 50-ft MCI coach. Field trips were made to transit agencies to gather information about existing bus subsystems, and the effects of the existing vehicle subsystem designs on the integration of VAA systems into buses were assessed. Such information was used to define the interface and to determine the interface requirements.

The identified interface between VAA subsystems and existing vehicle subsystems included 1) the interface between the VAA actuator and the existing steering system (including the power steering system) of the buses, 2) the interface between the VAA control computers and the existing controller area network (CAN) bus on the transit buses, and 3) the interface between the VAA subsystems and the electric power system of the buses. Subsequently, the interfaces between VAA subsystems were also identified based on the functional block diagram of the VAA system. The interface requirements were then developed for major functional blocks to cover the performance, such as accuracy, range, update rate, time delay, redundancy, etc., as well as the mechanical installation, electrical power supply, and data communication messages and message properties.

Finally, the interaction between vehicles and the infrastructure was addressed. Since minimum modification to the existing infrastructure was preferred in this VAA project, the interface requirements assumed no modification in the design of existing running way, stations, and vehicle exterior geometry. The vehicle-infrastructure interface design then focused on the infrastructure-based references for magnetic marker sensing and the DGPS/INS positioning. Interface requirements, such as the distance between magnetic markers, their depth below the road surface, the location of Global Positioning System (GPS) base stations, etc., were provided for the two sensing technologies.

The system requirements and interface requirements guided the development of the VAA system, from the selection of each individual system component to the performance evaluation of subsystems, VAA functions, and the overall VAA system. Since the VAA project was one of the first deployments of VAA systems in revenue service, these requirements will be highly valuable in serving as guidelines for the development and deployment of future VAA systems.

In the development phase of the VAA project, all components of the VAA systems were designed, developed, and verified through component testing and component integration testing. The key components of the VAA system include the steering actuator, magnetic sensor modules, the DGPS/INS module, the control computers, and the HMI. The steering actuator interfaces with the bus's power steering system so as to provide steering for the lane-keeping and precision docking functions. It receives control commands from an upper-level controller (residing in the control computers) and actuates the existing steering system to the desired steering angle. The magnetic sensor modules and the DGPS/INS module are the two vehicle positioning sensing technologies employed in this project to detect the vehicle position with respect to the lane center. The control computers are the brain of the VAA system; they receive commands from the driver through the HMI and relevant sensing information from the sensing systems and then determine the appropriate steering commands and send them to the steering actuator to achieve the desired maneuvers. The HMI modules are the bridge or communication channel between the driver and the VAA system; they receive inputs from the driver and generate the corresponding commands to the control computers and also receive the status information from the control computers and provide that information to the driver.

As the VAA system adopts modular design architecture, all the above key components except the control computers were designed as individual embedded systems. The embedded software modules reside in individual embedded systems to perform the specific functions of the module and to interface with other key components. For example, the magnetic sensor processing software resides in the magnetic sensor module; it processes magnetic sensing information, calculates the lateral position, and communicates the calculated lane position together with magnetometer health information to the control computers through a dedicated Controller Area Network (CAN) bus. Two PC104-based control computers, each with its own separate power supply, were designed to perform sensor fusion, lateral control, and fault detection and management. They also communicate with each other and other system components through the CAN buses.

To ensure that all key components meet the respective technical specifications that satisfy the VAA system requirements and the integration requirements, component testing and component integration testing were conducted. These tests also served as means to identify and expose any issues with the design, implementation, interface, and integration to assess the associated risk to the project early on and to ensure that all issues are addressed in an appropriate manner. The component testing focused on the functionality of the individual components, including features such as sensor range, performance capability, mechanical design, mechanical space, mechanical assembly characteristics, embedded processor speed and throughput, interface, working environment, and power specifications. The component testing adopts a "requirements testing" approach, in which each component is tested and checked against its requirements and specifications. Moreover, two basic types of testing—component unit testing and component acceptance testing—were conducted in iterations to correct and resolve any bugs or problems.

Upon the success of the component testing, the component integration was first performed with a 40-ft test bus at PATH, which included the installation and functional evaluations of the software operating environment, firmware, software drivers, sensors, and data communications. The component integration testing was conducted to ensure that all components function according to the technical specifications and that the integration subsystems satisfy the functional requirements and interface requirements. After testing on PATH's 40-ft bus, the verified integrated VAA components were migrated to the VAA test buses from LTD and AC Transit.

Upon the completion of the component integration testing, the project entered its third phase, the deployment phase. The LTD bus was used to conduct most of the system validation testing. The goal of the system testing was to ensure that the VAA system reliably performed as specified and that it implemented the functions and protocols to deal with anticipated faults. Moreover, the system testing also aimed to validate the robustness, safety, and usability through systematically designed experiments. Such system validation tests were necessary to ensure that the VAA system works correctly and consistently before conducting the field operational test (FOT) with revenue passengers from the general public.

The system validation tests were conducted in two stages: tests for VAA performance characterization and tests for VAA robustness validation. During the tests for VAA performance characterization, the baseline system performance was established by calibrating sensor and control system parameters and tuning system performance, first on test bus at small test tracks and then on transit test buses on the selected transit routes. During the tests for VAA robustness validation, each transit test bus was driven along the selected transit routes for sufficiently large number of runs and the performance measurements were collected by the onboard data acquisition system. These measurements were analyzed to evaluate the consistency and robustness of the VAA system.

The performance testing verified that, despite the variations in vehicle speeds, the LTD bus maintained very consistent lateral deviations from run to run. The docking accuracies for all six platform edges of the three Emerald Express (EmX) route BRT stations equipped (one eastbound and one westbound for each station) were within +/-2 cm to the desired lateral positions (standard deviation [STD] < 1 cm) for both the very sharp (25–35 m radius) and the relatively mild (~100 m radius) docking curves. Similarly, the VAA system for the AC Transit applications kept the bus close to the center of the lane (better than 10 cm) while the bus negotiated sharp curves and brought the bus straight and parallel to the platform with the lateral deviation within +/-1 cm consistently (tested only on the test track at RFS). The fault testing demonstrated that 1) all faults were quickly detected, and each fault was detected by multiple detection mechanisms; 2) all control transitions were seamless, including the one between the two control computers; and 3) the driver easily took over the control within a few seconds after the warning started.

The operation phase followed the successful system testing of the LTD applications. The operational phase included driver recruitment, driver training, public outreach, and FOT testing. PATH was responsible for providing the baseline training materials and generating guidelines of the driver training as well as training the instructors/trainers for the transit agencies. The transit agencies recruited the operators, supported the overall training logistics, and integrated the VAA driver training into their own driver training procedures. More than 30 operators were trained and had used the automated bus in revenue service.

Since deploying an automated steering function on a transit bus was still a relatively novel concept for US transit agencies and operators, very limited experience with such deployment exists in the industry. Therefore, the development of driver training in this project became a combined effort among the VAA system developers, the transit agencies, and the drivers who participated in the testing and training processes. The training procedure and background information was first developed to provide an overview of the VAA system, its operations, and the corresponding driver interface. Detailed training sessions were then conducted with a few instructors selected by the transit agencies, whose feedback was incorporated into the training procedure and material; after the procedure and material were delivered to the instructors, they further updated them in accordance with the existing transit agency training procedure. The general group of the drivers who will use the VAA system during revenue service would then be trained by those instructors with the modified training process.

Before revenue service operations, the LTD bus first went through a no-passenger operational test for 1.5 months for further validation of the system performance and reliability. Subsequently, a LTD media event was held on June 9, 2013, and revenue service operations started on June 10, 2013, in Eugene, with the VAA system activated. Data collection and analysis were conducted to support the VAA program goals; both objective data and subjective data were collected. The objective dataset included quantitative performance data and transit property record keeping, and the subjective dataset included perceived performance and reliability of the driver and the passengers.

The quantitative system performance data were recorded by the onboard data acquisition system. To evaluate and identify the performance of the VAA system, these data were analyzed to investigate tracking accuracy, ride quality/smoothness, system robustness, system availability, safety-related observations, fault management events, driver response to events, and changes in behavior for other driving tasks. The data were also provided to an independent third party for an evaluation of the VAA demonstration.

Data from revenue service operations consistently demonstrated that the VAA system achieved superior performance over manual driving. For the lane-keeping, the lateral deviation achieved by the VAA system had a standard deviation less than half of that achieved by manual steering. The monthly standard deviations of the lane-keeping lateral deviation were between 6.07 cm and 7.68 cm for automated steering, and the monthly standard deviations of the lane-keeping lateral deviation were between 14.79 cm and 16.84 cm for manual steering. For precision docking, the standard deviations of the docking errors at the six stations for the manual steering ranged from 4.18 cm to 7.15 cm, and the standard deviations of the docking errors at the same six stations under automated steering ranged from 0.73 cm to 1.02 cm. (The slightly higher standard deviation of the docking errors for the VAA system occurred during the time when the radius road bushings of the bus were blown, which caused the bus to warp.) In addition, the data indicate no noticeable impact of the automated steering on general operating speeds.

Furthermore, the VAA system itself did not experience system or component failure during the revenue service period. As a result, driver intervenes due to VAA system fault did not occur in the six-month revenue service. The VAA system, however, correctly detected faults (via monitoring bus J1939 CAN and sensor health) induced by several different failures in the bus's own power system and warned the operator accordingly. The revenue service and those incidences demonstrate that the VAA system is reliable and its fault detection and management functioned correctly. Regarding false alarms, the VAA system generated about one false alarm per month, on average, each of which lasted less than 0.5 sec and created one short beep; operators did not take any action given the short duration of the false alarms.

Finally, this VAA project was one of the first vehicle automation projects that dealt with many real-world deployment issues, including (a) substantial new development of hardware and software for improved reliability and safety; (b) development process for product-like components and subsystems to meet the requirements of revenue services; (c) deployment issues such as project delivery, as well as infrastructure, maintenance, and operational preparation; (d) close collaboration with transit agencies and bus operators during the development phase; (e) application and assessment of real-world operational scenarios; and (f) complexities in contractual arrangements with transit agencies and multiple industrial partners.

Analysis of the data from the system testing and revenue service at LTD's EmX route as well as the experiences gained from resolving the real-world issues provided the following key findings:

- Safety design is the first and foremost design consideration for deploying an automated bus in a public roadway, and safe operation is the prerequisite for transit agencies to adopt any automated control technologies into a bus for revenue service.
- Safety design in vehicle automated control is a complex and iterative process in which the following factors are all very critical: redundancy, fault detection and warning, degraded-mode controls, fault test procedures, and software interlocking to ensure the system is operating under the correct version of the system.

- The VAA system calls for the use of appropriate materials and installation procedures. Smaller but stronger rare-earth magnets were selected to avoid re-bars under concrete sections of roadway to avoid interference. In addition, it was discovered that epoxy sealant over the embedded magnets did not properly cure when installed in wet-weather conditions; some needed to be reinstalled at a later date. During the course of the project, the magnetic sensor bars on the LTD bus had to be replaced due to corrosion from bus washing and weather conditions.
- The VAA system creates a "train-like" operation by following the magnet track. With a "fixed" track, the feel of the ride is determined by the speed. Thus, it exhibits somewhat different "steering characteristics" to which the operator must learn to adapt.
- The VAA system maintains a consistent docking performance, and initial comments from the operators suggest the VAA system reduces operator stress with improved performance.
- The deployment of an automated bus for revenue service elevates the development and installation processes to be similar to those of a product-like system. Revenue service operations requires that the design, development, and deployment processes address all possible issues that may occur in real-world situations.

The project also experienced several long project delays from its beginning, including a one-year delay due to a prolonged subcontract process and liability issues of the subcontractors, a one-year project suspension for resolving the contract and liability issues between the University of California and Caltrans, three months of accumulative unavailability of the buses that resulted from several maintenance problems, seven months of effective delays due to the loss of key engineers in the middle of the project, and at least six months of additional effort for safety reinforcement due to the enormous challenges of developing a safe automated steering system for bus revenue service (the first such system in the US). Because of these delays, the project accomplished only roughly 10 months of revenue service (June–October 2013 and October–February 2015, with a one-year project suspension in between) for the LTD automated bus during a period of 1.7 years (June 2013–February 2015).

Although the component integration and initial system testing were completed for the AC Transit MCI coach, in the end, the system was not tested along the HOV lane on SR 92 due to the unresolved contractual issues between the University of California and AC Transit, as well as the very limited time and resource left for the project.

Upon conclusion of the project, the following are the recommendations from the team:

- Safety standard ISO 26262 should be adopted in the design, development, and deployment of the VAA system for the transit agencies.
- For this VAA system to be ready for larger-scale deployment, it needs to go through one more design and development iteration so that new technology and sensors can be incorporated and system architecture can be further enhanced to support the safety design.
- Future development and deployment of VAA systems should include commercial industrial partners.

SECTION 1

Introduction

Transit agencies throughout the United States are facing mounting challenges related to the provision of high-quality and cost-effective public transportation solutions for the public. Transit agencies need to offer convenient and reliable mobility options for customers at a reasonable cost to the transit agency and locality. Due to the increased cost and constraints on land use in many metropolitan areas, adding significant lane-miles of roadway is becoming increasingly difficult. Transportation agencies are investigating means to maximize available capacity without incurring significant additional costs for new construction. High-quality public transit service should be seen as a viable alternative for regions in which congestion is severe and the potential for significant mode shift could be realized.

Among the transit options, bus rapid transit (BRT) is seen as a cost-effective alternative to more conventional fixed guideway systems that are becoming increasingly expensive to construct and operate. As current funding (federal, state, and local) for conventional fixed guideway transit is becoming more limited, transit agencies have to come up with more cost-effective alternate modes. In the recent development of BRT systems, in which new construction does not take place, new BRT lanes are being carved out within existing right-of-way (ROW) constraints. In 2003, Las Vegas re-striped North Las Vegas Boulevard and devoted a lane to transit operations, and Minneapolis has an ongoing and aggressive program to convert freeway shoulders to transit-use lanes. Because of the land-use, cost, and institutional constraints, BRT-interested transit agencies have expressed strong desires for technological means that would allow buses to travel safely on narrow ROW, which could not only reduce construction and acquisition costs by as much as 20%, but could also allow for a bike lane or parking lane on arterial roads. In some cases, a few feet of lane width reduction could affect the decision of whether a dedicated bus lane can be provided.

Vehicle Assist and Automation (VAA) systems offer the opportunity of providing high-quality transit service within reduced lane widths. VAA includes four functions that can transfer portions of the bus driving responsibility from the driver to the VAA system: VAA Precision Docking (VAA-PD) provides for precision docking at bus stations, VAA Vehicle Guidance (VAA-VG) provides for vehicle guidance or automatic steering on the running way between stations, VAA Platooning (VAA-P) provides for automatic platooning of buses at close separations, and VAA-AVO provides for fully-automated vehicle operations. The VAA-PD function can facilitate passenger boarding and alighting at stations. VAA-VG could support reduced lane width, allowing the bus to operate in a designated lane that is only slightly wider than the bus itself without increasing driver workload; it could be implemented in partially- or fully-automated modes to guide buses through narrow bridges, tunnels, toll booths, and roadways, as well as bus stops, tight curves, and designated trajectories in maintenance yards. The primary emphasis in this report is on the VAA-PD and VAA-VG systems, which are expected to be the first to enter public use. The issues identified for these systems, in large part, should be applicable to the more advanced VAA systems as well.

Stakeholders have shown significant interest in VAA. For transit agencies, VAA offers significant benefits including the delivery of rail-like service—an attractive feature to riders—at a fraction of the cost. BRT buses equipped with VAA technologies could provide a similar level of service as conventional fixed guideway systems with the same, if not more, benefits. From the driver perspective, the VAA system can be a means to decrease workload and stress and, at the same time, allow operation in more challenging environments (e.g., narrower lanes). For passengers, the implementation of a VAA system will mean smoother operation, faster and safer boarding and alighting, reduced travel time, better schedule reliability, and increased mobility for Americans with Disabilities Act (ADA) riders.

VAA Project Scope

To address the needs of the transit industry, the U.S. Department of Transportation (USDOT), through the Federal Transit Administration (FTA) and the Intelligent Transportation Systems Joint Program Office (ITS JPO), have spear-headed efforts to analyze the impacts that VAA systems would have on bus-based transit systems. The project, called the VAA Tier II Exploratory project, completed in December 2005, looked at the potential impacts of VAA technologies on transit operations. The results of this research are promising, showing that five out of seven typical revenue service operating scenarios would benefit from VAA technologies and that there is a defined market for VAA technologies [1]. The seven revenue service operating scenarios include suburban collector, urban circulator, mixed flow lanes, designated arterial lanes, roadway shoulder operations, at-grade transitway, and fully grade-separated exclusive transitway. The five operating scenarios that would benefit from VAA technologies are ranked as follows beginning with the greatest level of benefits: 1) designated arterial lanes, 2) urban circulator, 3) fully grade-separated exclusive transitway, 4) at-grade transitway, and 5) mixed flow lanes.

Research and development on VAA technologies have been conducted for many years. Key VAA technologies such as lane assist systems have been developed, and prototype systems have been developed and demonstrated. In most cases, full technical feasibility and the benefits have not been quantified yet, and extrapolating results from small initial demonstrations to revenue service is generally not convincing. However, the technical merits and benefits of these technologies could be fully quantified in a broad demonstration involving revenue service. FTA is specifically interested in demonstrating two viable VAA applications that have been identified in recent research as having the most potential—precision docking and lateral guidance. These are core applications that VAA systems could enable in different transit operational scenarios. Different operational scenarios would require different configurations or combinations of these applications, such as precision docking at bus stops on local streets or a combination of precision docking on local streets and lateral guidance on a narrow shoulder or other exclusive lane.

In 2009, FTA and the USDOT ITS Joint Program Office initiated the VAA demonstration project. The California-Oregon team including Alameda–Contra Costa Transit District (AC Transit), Lane Transit District (LTD), and the University of California Partners for Advanced Transportation Technology (PATH) were selected to conduct the VAA project. Caltrans contributed significant cost share funding throughout the project. The objective of the VAA project was to demonstrate the technical merits and feasibility of different VAA technology applications in bus revenue service, and to assess their costs and benefits. Caltrans partnered with AC Transit, LTD, PATH, and several private sector companies. Caltrans planned to demonstrate the VAA applications of bus lateral guidance (also referred to as lateral control, and lane-keeping) on a high-occupancy vehicle (HOV) lane and through a toll plaza and lateral guidance on a BRT busway and precision docking at BRT stops. According to the plan, these applications would use the two VAA sensing technologies: 1) magnetic marker sensing and 2) Differential Global Positioning System/Inertial Navigation System (DGPS/INS).

Specifically, the project team planned to test BRT lane-keeping and precision docking at bus stops on LTD's Franklin EmX BRT route and lateral control on an HOV lane and through a toll booth on AC Transit's M line. The AC Transit M line connects Castro Valley, Hayward, and Union City with San Mateo and Santa Clara counties, crossing the San Mateo–Hayward and Dumbarton bridges. A three-mile section of HOV lane on SR 92, from Hesperian Boulevard to the San Mateo Bridge toll plaza, and a narrow toll lane were equipped for vehicle lateral control, and one 50-foot MCI coach was equipped. The bus can make four round trips per day. The original LTD Franklin EmX BRT service operates on a four-mile route between Eugene and Springfield in Oregon, with a largely dedicated ROW. It has eight intermediate stations and two terminal stations. The second EmX corridor, adding one more terminal station at Gateway with 7.8 additional miles, began operation in 2011. Buses operate at 10-minute headways during peak periods and 20-minute headways off-peak. One 60-ft articulated New Flyer bus was equipped with the VAA technology for testing precision docking at three BRT stations and lane-keeping on a 1.5-mile segment of the route between the equipped stations. The bus can make 15 round trips per day. Although the system integration tests were completed for the AC Transit MCI coach, the field operational test was not conducted along the HOV lane and toll booth on SR 92 due to unforeseen project delays and unresolved contractual issues between the University and AC Transit.

In the context of this project, the VAA system consisted of lane-keeping and precision docking functions. The project was implemented in four phases: design, development, deployment, and demonstration field operational test. The detailed objectives and major tasks in each phase are described as follows:

- **Phase 1, Design** – The objective of Phase 1 was to finalize the VAA technical requirements, system architecture, and design. During this phase of the project, the VAA performance targets, system requirements, and component specifications, which were developed by the project team together with several transit agencies prior to this project, were refined. A modular VAA system architecture and designs at both system and component levels were created. Plans for development, deployment, and operation were developed. The design phase was completed initially in 2009; a number of design modifications (especially in the area of safety) were made during the subsequent development and deployment phases as various operational and environmental issues were discovered and resolved.
- **Phase 2, Development** – The development phase included all hardware and software component design, fabrication, and initial testing. The main hardware components included the steering actuator, magnetic sensor bars, DGPS/INS units, controller computers, the human-machine interface (HMI), system power supplies, data recording devices, and interfaces. The software modules included magnetic sensor processing, DGPS/INS integration, steering actuator servo, magnetic/GPS sensor fusion, Controller Area Network (CAN) bus and other interfaces, dual control computers, multiple lateral and switching controllers, HMI warning algorithm, and data recording, as well as fault detection and management. PATH was responsible for the higher-level application software development and control computer. ContainerTrac was responsible for the development of embedded systems. The University of California at Riverside was responsible for the development of GPS/inertial measurement unit integration. IMI was responsible for the initial decision on the control computer. In Phase 2, the first sets of hardware components as well as baseline software modules were identified. The hardware components as well as their related software drivers and modules were implemented first on the PATH bus and then on the LTD bus. The existing New Flyer buses at PATH served as the initial test platforms for new components and for hardware wiring, mounting brackets, and installation strategies. The initial debugging of the hardware components with their associated software drivers and other related software was conducted at the PATH test track at the Richmond Field Station (RFS). Concurrently, PATH worked with LTD and AC Transit on roadway survey and magnet installation issues on the intended routes. PATH worked with survey contractors to specify the magnetic

reference locations and created digital maps of the test sites. The installations of the magnets were done by contractors, which started during Phase 2 and was completed at the beginning of Phase 3.

Since the subcontracts with the key subcontractors were completed towards the end of 2009 and beginning of 2010, the hardware components were designed, developed, fabricated, and tested in 2010. The components were individually benched-tested and first installed in the PATH test bus for system interface and finally into the LTD New Flyer 60-ft bus in December 2010. The LTD and AC Transit magnetic tracks were designed and installed in December 2010 and May 2011, respectively. The LTD yard track for system debugging, software verification, and fault testing was installed in June 2011.

- **Phase 3, Deployment** – The objectives of Phase 3 were to complete and confirm the VAA system performance and reliability through testing and to instrument the additional (AC Transit) buses based on the lessons learned from the first installation and initial testing conducted in Phase 2. According to the original plan, all system performance and operations were to be tested and validated at the test track at RFS in an iterative fashion, from simple to complex operations, before driving on the operational test routes. However, many unexpected operational, environmental, and safety issues were discovered during the initial testing phase at LTD. System performance capabilities that required repeated testing included precision docking, lane guidance, driver training, failure detection, and emergency driver warning and reactions were done on the LTD yard track. After subsystem and system level testing were carried out on the RFS and LTD yard test tracks, testing commenced at the public operational testing site.

  It is worth noting that many operational situations and environments could occur only on public roads and, thus, could be tested only in real-world conditions. Because safety is the most important consideration while testing on public roads, system safety management functions needed to be in place before any closed-loop control could take place. The basic safety management functions included fault detections and management, as well as redundant operations. Strict testing protocols and safety procedures were found to be critical to prevent software operational errors and were developed and followed throughout the deployment phase.

  The component integration testing was completed in 2011; the closed-loop performance (with limited safety software) was first validated in June 2011 on the LTD yard test track. An additional six months were required to put the basic safety software in place to enable the public road testing on the EmX track. During the first half of 2012, the team focused on resolving and strengthening the subsystem functions and validating the reliabilities based on the testing on the EmX track. The automatic steering control testing began in July 2012, and lane-keeping and precision docking performance was validated in November 2012. The final safety system was re-evaluated, improved, and repeatedly tested by injecting faults for another five months. The system was ready for operation by LTD in April 2013. Parallel to completing the above tasks on the LTD test bus, the VAA components were installed on two AC Transit test buses in October 2011. The system integration and verification tests were completed using the RFS test track between August and October 2013.

- **Phase 4, Operation** – The objectives of this phase were to use the VAA applications in revenue service to demonstrate and document the costs and benefits to transit operations. Phase 4 started with the finalization of the operational testing plan by the stakeholders, especially the host transit agencies. Individual testing scenarios, reporting and calculating methods, and test schedules for the operational test sites were defined, designed, conducted, and reported in close collaboration with the transit agency partners. Throughout the field testing process, policy, legal, and institutional evaluations were conducted in addition to the technical evaluations. The VAA team worked with an independent entity in the evaluation of the VAA applications—the National Bus Rapid Transit Institute (NBRTI) at the University of South Florida's Center for Urban Transportation Research (CUTR). Specific responsibilities were identified at the beginning of the VAA demonstration project.

  For LTD, driver training and VAA operations without passengers were conducted in April and May 2013. Regular revenue service operations (with passengers) started in June 2013. VAA revenue service operations were suspended between October 2013 and October 2014 due to contractual and liability issues. VAA revenue service operations started again in October 2014 and ended in February 2015 based on the final schedule of the project. Contractual issues between the University and AC Transit were never fully resolved, thus prohibiting the re-start of the AC Transit testing and VAA revenue service operations along SR 92.

As it was not practical at the proposal stage to anticipate many real-world issues such as major institutional and contractual complications, the project experienced significant delays from the initial schedule during the course of the VAA project. Most of these delays were out of the control of the technical team, which did its best to minimize schedule impacts. Project delays included a one-year delay due to the prolonged subcontract process and liability issues of the subcontractors, a one-year project suspension for resolving contract and liability issues between the University of California and Caltrans, three months of accumulative unavailability of buses due to maintenance problems, seven months of delays due to the loss of key engineers in the middle of the project, and at least six months of additional effort for safety reinforcement due to the enormous challenges of developing a safe automated steering system for bus revenue service (the first such a system in the US).

As the result, the initial project plan was modified to accommodate the schedule deviation and the constraints that the project was not able to overcome. Despite the difficulties, the project team achieved the primary objectives of the VAA project and successfully conducted the first field operation test of the VAA system in the US.

VAA System Overview

This section provides the definition of major VAA system components and applications and a description the functional blocks for the VAA system. In addition, since the VAA system is designed as an add-on/retrofit system, the existing bus system is also described in this section.

VAA System and Application

The VAA system provides automated steering or driver assistance functions to help maintain a transit vehicle in a designated lane or a desired trajectory. VAA systems can be used in BRT applications such as precision docking, lane guidance, lane-keeping or lane-changing, and longitudinal control, as described below:

- Precision docking – Controlling a vehicle to dock in precise locations at a bus stop or platform. With bus stops constructed in a train-platform manner, automated precision docking can deliver accurate, reliable, and repeatable maneuvers that allow safe, convenient, and expedient boarding and alighting operations.
- Lane guidance – Using VAA systems to provide driver with information such as vehicle position relative to the travel lane or the desired path. Lane guidance is applicable and particularly useful in driving conditions in which visibility is poor or limited. Example applications are wide vehicles traveling on narrow roadways and bridges or through narrow toll booth lanes.
- Lane-keeping or lane-changing – Driving vehicles on selected lanes or making transitions between lanes. This can be implemented to maintain vehicles in narrow pathways so that the width of lanes and, thus, the infrastructure use and costs can be proportionally reduced.
- Longitudinal control – accelerating or braking. The use of speed control is optional for VAA functions; for example, the VAA system developed in this project does not provide longitudinal control functions. However, for certain applications, it is advantageous to integrate both the lateral and longitudinal functions for performance requirements. For example, in precision docking with longitudinal control, the bus speed can be controlled so that it not only will approach the station with smooth speed profile but also will stop at a pre-designated location of the docking station to facilitate passenger boarding and alighting.

VAA System Functional Blocks

The VAA system can be partitioned into several functional blocks. Figure 1-1 is a functional block diagram of the VAA system, with information flows between functional blocks and interactions with the driver, the existing bus subsystems, and the infrastructure. The VAA system is composed of the following functional blocks:

- Sensing/Communication – Sensing directly interacts with existing bus components and with external infrastructure support to provide information on vehicle states and position. Information also can be exchanged between the vehicle and roadside and among different vehicles through wireless communication. In Figure 1-1, the solid lines between the components represent physical connections for the information exchange. The dashed line between the sensing and the infrastructure as well as that between the bus driver and the infrastructure indicates that no physical connections are involved; instead, the information is obtained through sensing of the magnetic field, visual sensing, and wireless communication.
  - Vehicle state sensing – the components in this category potentially consist of existing or additional vehicle sensors. The vehicle state information includes vehicle speed, vehicle yaw rate, door opening, etc. It provides necessary information for controller and fault detection/management.
  - Vehicle position sensing – through interaction with sensor reference infrastructure, vehicle position sensing detects the vehicle position with respect to the lane center. It is the key sensor in Vehicle Assist and Automation-Precision Docking (VAA-PD) and Vehicle Assist and Automation-Vehicle Guidance (VAA-VG) systems. The VAA system in this project employs both magnetic sensing and GPS for vehicle position sensing.[2]
  - Communication – roadside-to-vehicle, ground-based, or satellite-based broadcast communication provides differential signals for DGPS.
- Actuating – since the VAA system in this project provides automated lateral control only, the driver controls the speed through the existing vehicle engine/transmission system as well as the existing pneumatic brake system. Therefore, the VAA system includes only one actuator, the steering actuator, to interface with the bus's power steering system so as to provide steering for the lane-keeping and precision docking functions.
  - *Steering actuator* – the steering actuator receives control commands from an upper-level controller and actuates the existing steering system to the

[2]The LTD deployment tested the magnetic marker sensing technology only. The AC Transit deployment planned to test both sensing technologies, each as a primary source and the other as a backup; however, the project ended before the AC Transit applications became operational

– desired steering angle. This is the key actuator in a VAA-PD or VAA-VG system. It can also be used as a haptic device, providing torque feedback to alert the driver.

- Controller – the controller is the brain of the VAA system. It receives commands from the driver through the HMI and relevant sensing information from the sensing systems. Appropriate commands are then calculated and sent to the actuators to achieve the desired maneuvers.
  - Lateral controller – the lateral controller calculates the steering command that is sent to the steering actuator according to the received sensor information so that the bus stays within the lane boundary or close to the docking platform.
  - Planning and coordination controller – the planning and coordination controller issues commands to the lateral controller based on the current bus positions with respect to the lane center, driver commands, transit operational rules as well as the states of the fault detection to achieve the desired bus maneuvers (e.g., lane-keeping or precision docking).

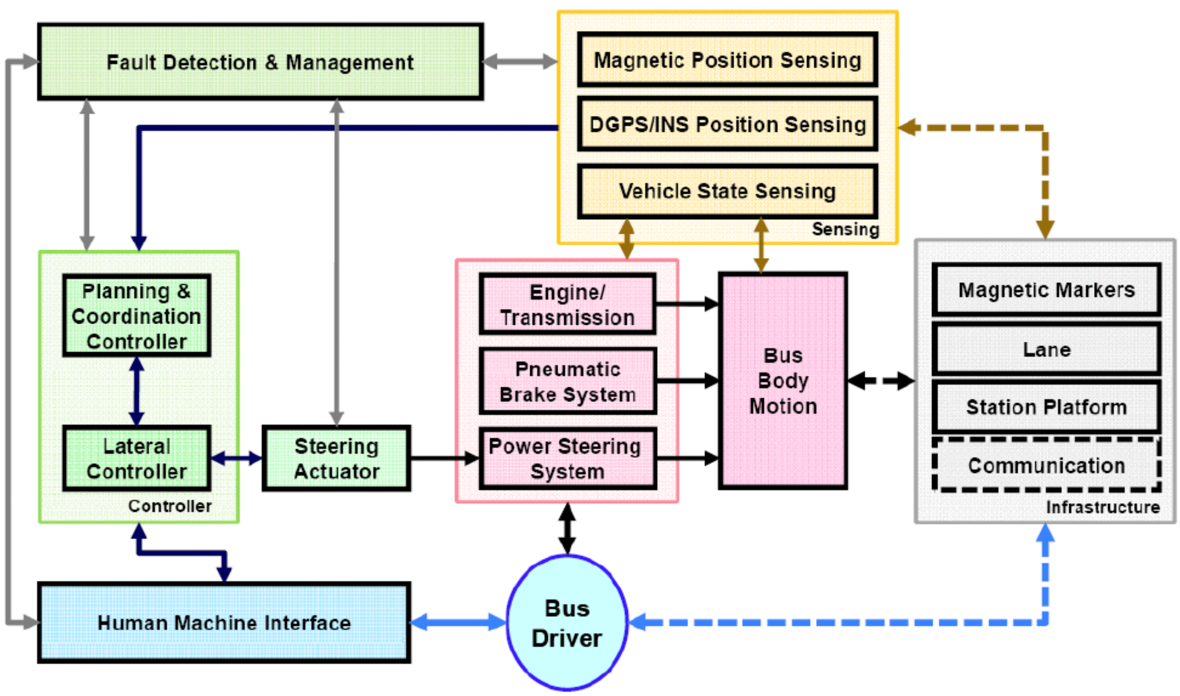


Figure 1-1

Functional block diagram of VAA system

- HMI – the HMI is the bridge or communication channel between the driver and the VAA system. It can serve multiple functions, including providing diagnostics, warnings, driver assistance, and system activation or deactivation via multiple modalities (audible, visual, or haptic feedback to driver).
- Fault detection and management – this forms a necessary functional block for the VAA system because it is a safety-critical system. Alerts are issued to the driver when failures and inconsistencies are detected in sensor, actuator, or controller functioning. The VAA system will then operate in a failure mode with degraded performance with guaranteed safety.
- Infrastructure – a VAA system includes the special characteristics of the lanes themselves, which may include dedicated lanes and docking platforms as well as visual or magnetic lane markings for sensing. Typical vehicle position sensing mechanisms generally require infrastructure support of some sort. The VAA system in this project employs magnetic sensing and DGPS; the former requires magnets be installed along the BRT route and the latter requires roadside differential stations and communication means to provide the appropriate differential signals to the on-board GPS receivers.

Generally, the VAA system operates as follows:

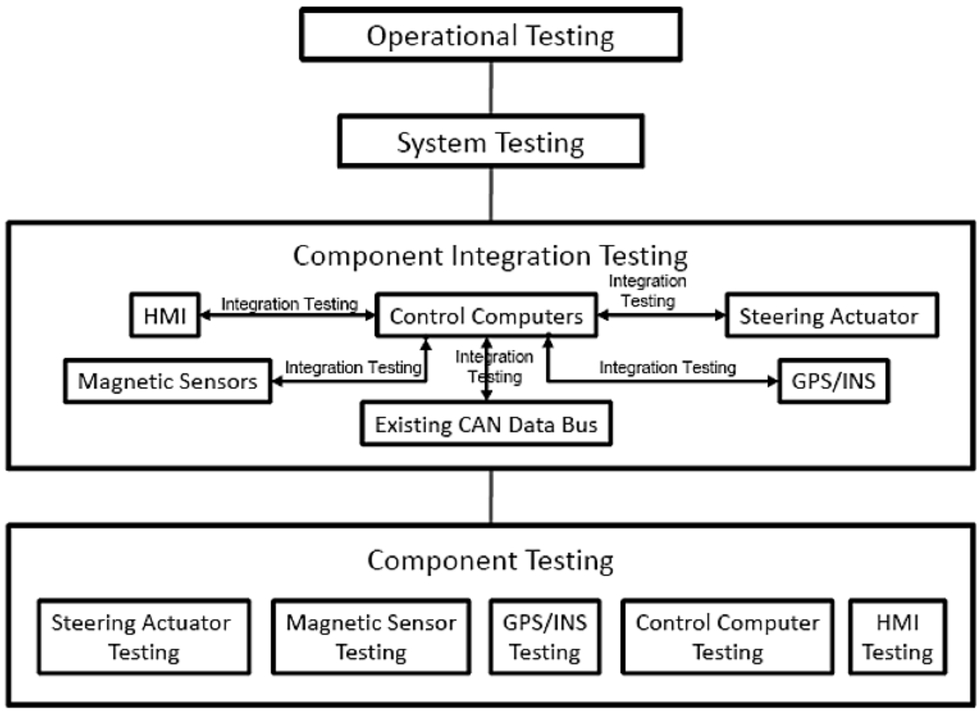
1. The bus driver monitors and controls the VAA system activation through the HMI.
2. The sensing/communication block obtains information such as vehicle lane position, related vehicle states (e.g., vehicle speed, yaw rate, etc.), and GPS differential information from its interactions with the sensing infrastructure, data communication with existing bus subsystems, other VAA subsystems, and wireless communication with other buses and the roadside.
3. The acquired sensing information is made available to the controller, HMI, and fault management subsystems through data communication.
4. Once the controller receives the information, control commands are calculated and sent to the corresponding actuators when the driver has properly activated the VAA functions.
5. The actuators actuate existing bus subsystems, such as the power steering system for the VAA system, according to the received commands so that the desired vehicle maneuver (e.g., lane-keeping and precision docking) is achieved.
6. The fault detection and management block continuously monitors both lower- and upper-level system operations and provides warnings to the driver through the HMI when failures or hazardous environmental conditions occur.
7. The lane-keeping and docking functions are maintained, if such degraded operations are possible, before drivers take over.

VAA Testing

Figure 1-2 provides an overview of the four hierarchical levels of testing involved in the VAA project: 1) component testing, 2) component integration testing, 3) system testing, and 4) operational testing. The hierarchy represents both the functional relationship and the sequential schedule of these testing levels; each level of testing directly supports and precedes the testing at the level right above it. The component integration testing is above the component testing; and it is the prerequisite of the system level testing.

Figure 1-2

Overview of testing involved in VAA project



Component testing was to ensure that all key components functioned appropriately and satisfied the corresponding component specifications as defined in the VAA system and interface requirements (Section 2). Component testing was conducted jointly by the VAA system engineers at PATH and the component developers.

Component integration testing followed component testing; it focused on testing the interfaces among all key components. The interfaces were tested with the basic application software that resides in each component when such application software became available. PATH worked together with the component developers to determine the wiring and hardware installation strategies. An existing 40-ft New Flyer bus at PATH was used as the testing platform for the component integration. The component integration included installation and functional evaluations of the software operating environment, firmware, software interface drivers, sensor calibrations, debugging and development tools, and data communications. After testing on PATH's 40-ft bus, the verified VAA components and systems were migrated to VAA test buses from LTD and AC Transit.

The system testing was the next level of testing after the component integration testing. The purpose of the system testing was to ensure all VAA system functions were carried out according to the system requirements [2]. Extensive subsystem and system-level testing was iteratively conducted first on the RFS test track using PATH's 40-ft test bus and then using the instrumented VAA test buses. Subsequently, multi-layer functional and multi-period reliability testing was conducted for each component, subsystem, functional algorithm, operation scenario, and bus. The goals were to establish baseline performance capabilities and to verify the system and component reliability and robustness. Finally, system testing was conducted on the VAA operational routes to calibrate sensor and control parameters, tune system performance, and verify the performance and operations for the respective revenue operations on the selected LTD and AC Transit routes.

Field operational testing was the highest testing level of the VAA project; it included testing on the operational routes first without and then with passengers. Before the operational testing, the system was introduced to the drivers of the local transit agencies. Workshops and driver training were conducted with support from transit agency management and the drivers' union to ensure that drivers understand the operation of the VAA system. Discussions and test rides were carried out among the system developers, transit agencies and their drivers, state agencies, and an independent evaluator. Based on these discussions, the system operation procedures and the operational test plan (including the data collection and analysis procedures) were adjusted. Initial test runs on the VAA revenue service routes were then conducted without passengers until predefined reliability criteria were reached. Since any critical bugs had been resolved during the system testing, a relatively small number of bugs was discovered and fixed during this initial operational testing phase.

Upon successful completion of testing without passengers, revenue service testing with passengers was conducted for the lane-keeping and precision docking applications for LTD in Eugene; field operational testing for AC Transit was not carried out due to contractual issues. Quantitative measures, including lateral sensing and control accuracy and ride quality measures, were collected using an on-board data recording module. Qualitative measures were obtained through interviews with operators, drivers, and passengers and included perceptions of ease of use of the VAA system and the HMI design, operator and passenger comfort in automated operation and during transitions, and other general perceptions and comments.

Report Organization

The remainder of this report is organized as follows:

- **Section 2: Requirements** reports on the requirements for the VAA system, including general requirements for electronic guidance systems, detailed VAA system requirements, on-board interface requirements, and infrastructure-vehicle interface requirements. General requirements serve as a guideline for the system design and system and interface requirements development. VAA system requirements include safety and performance requirements for each VAA function and the technical specifications for each subsystem. VAA interface requirements describe the mechanical interface, power supply, and data communication for the key subsystems. The requirements on the interfaces between vehicles and infrastructure focus on the infrastructure-based reference support for accurate determination of vehicle position with respect to lane center.
- **Section 3: Development of Prototype VAA System** describes the key components, software modules, and software architecture, as well as the components integration of the VAA system. The VAA system consists of a number of key hardware modules and software modules. The magnetic sensor software module estimates vehicle position based on magnetic sensing, and the DGPS/INS software module provides position estimates by integrating DGPS and inertial sensor measurements. The steering actuator software executes motor control to turn the steering wheel. The HMI software module serves as a medium between the driver and the VAA system. The control computer interfaces with key components and implements the lateral control and provides commands for precision docking and lane-keeping functions.
- **Section 4: Component and Integration Testing** discusses the lower levels of testing. The component tests ensure that all key components function appropriately and satisfy specifications. The component integration tests make sure that all key components are properly integrated and meet the interface and performance specifications.
- **Section 5: Field Testing** discusses the higher levels of testing. The section first provides an overview of the test facilities at LTD and AC Transit and then describes the VAA driver training procedure, including background materials, provides operations guidelines for normal and emergency situations, and the protocols for the human subject study. The tests include system testing and field operational testing. The system tests validate that the VAA system is working correctly and consistently before the field operational tests can begin. Revenue service results provide VAA test results in LTD revenue service operations (testing in regular operations with passengers).

The field operational tests generated significant data and enhance the understanding of the VAA system in transit operations through collection and analysis of field data.

- **Section 6: Lessons Learned and Recommendations** presents the lessons learned from the project and provides recommendations.

SECTION

2

Requirements

VAA requirements include system performance specifications, technical specifications, and interface requirements. The performance and technical specifications define the operational conditions and environments and specify the performance, reliability, safety, and maintainability of the VAA system. The interface requirements ensure that the VAA system can interface seamlessly with the types of transit buses chosen for VAA applications. Interface requirements identify and define the interfaces among the VAA subsystems and with the bus. As the VAA system involves interactions between vehicles and infrastructure, the interface specifications also define interfaces between them to enable a successful design and implementation of the VAA system.

The VAA requirements were initially developed in two projects funded by FTA and Caltrans: Needs and Requirements for Lane Assist Systems for BRT and Interface Requirements for Lane Assist System for BRT. Under these projects, PATH collaborated with several transit and transportation agencies to conduct a series of workshops and follow-up discussions to determine the agencies' needs and past experience for transit operations as well as operational scenarios for VAA. Subsequently, detailed safety requirements, performance requirements, component specifications, and interfaces requirements were produced [2, 5]. In the VAA demonstration project, these system and interface requirements were adopted and improved to guide the development of the prototype VAA system for field operational testing.

General Considerations for VAA System Requirements

A VAA system should follow general design guidelines and requirements for electronic devices for vehicle applications and a set of new considerations for automated vehicle control systems. PATH research on this topic [2] has suggested that the general considerations for VAA system requirements can be grouped into the following six interrelated categories:

1. Safety
2. Performance
3. Reliability
4. Availability
5. Maintenance
6. Infrastructure requirements and modifications

Safety

Although VAA systems potentially can improve the performance of transit operations and help to reduce crashes and incidents, it is impossible to design an electronic guidance system to be free of faults or failures. Therefore, it is critical to understand the nature and potential consequences of these failures or faults so as to design a system to meet important safety criteria and, from a risk management perspective, manage the risk involving the introduction of new technologies.

- **Failures, faults, and their potential consequences** – Failures and faults can occur at any point in a VAA system. A number of hazardous consequences can develop due to system failures/faults, including but not limited to the following: 1) The VAA system suddenly causes the bus to deviate from its desired path with large lateral acceleration; 2) Driver take-over is expected but the driver is not given advance warning of this failure/fault and does not have adequate time to properly take over control; and 3) The driver mistakenly takes over and causes the vehicle to deviate from the desired path.
- **Fault management** – In theory, techniques are available for designing the VAA system to be highly reliable so that the occurrence of failures/faults becomes a very low-probability event. However, such a highly-reliable system may be cost-prohibitive. Alternatively, a VAA system can be designed to have the capability of either compensating automatically and safely for a failure or operating at a reduced level of efficiency after the failure of a component or power source. These modes can be implemented through the following means:
  - The system detects failure/faults prior to hazard consequence development. A built-in fail-safe process may lead the bus to slow down or bring the bus to a stop. However, this process will require the bus to have automated longitudinal control capability.
  - The system detects failure/faults with sufficient time to allow the driver to be warned and take control and either bring the bus to a stop or continue manual operation. A critical part of this handover is ensuring that the driver is prepared to take control of the vehicle. It may be necessary to first alert the driver of the failure and require some positive response on his/her part before handing over control, or the driver is required to have his/her hand near or touching the steering wheel. To adequately prepare for and respond to emergencies, a scenario-based system should be developed and used together with a fault tree analysis to develop ways and means that the system will respond to various situations.

Performance

Performance can be judged within three broad categories: ride comfort, tracking accuracy, and ease of operation. Ride comfort is essentially the smoothness of steering and, if the system is equipped with speed and braking control, smoothness of acceleration and deceleration. If the transit agency succeeds in attracting more riders, buses will tend to be more crowded, which may result in more standees, possibly with bikes, than on standard buses. It is important, therefore, that ride comfort with a VAA system be equal to, if not better than, that of a manually-driven bus. Additionally, unlike rail systems, buses are required to secure wheelchairs before the bus can move. If it is possible to prove that the ride that they provide is as smooth as a rail system, it may be possible to have the USDOT relax this requirement for VAA-equipped buses.

The second performance requirement for a VAA system is the level of tracking accuracy during both normal operation and docking at bus stops. Tracking that causes the bus to constantly weave back and forth to stay on track would seriously degrade ride comfort. Additionally, there are requirements specified in the Americans with Disabilities Act (ADA) for docking of light rail systems (maximum 3 in. horizontal and 5/8-in. vertical distance) that also would apply to VAA-PD-equipped buses and all other buses that satisfy ADA requirements. Previous discussions have yielded a general consensus that a maximum 2-in. horizontal gap would be acceptable as a performance target.

Ease of operation, relating primarily to the driver-vehicle (human-machine) interface (which should be independent of the chosen guidance technology), is another aspect of electronic guidance to consider. If operating a bus equipped with electronic guidance is materially different from a non-VAA bus, the question arises as to whether all drivers should be trained for operating VAA-equipped buses or just a select group.

The requirement to the electronic guidance provider, then, should be that the demands of driving a VAA-equipped bus are such that any professional driver can be trained within a reasonable amount of time. Thus, there should be no reason to have to give special status to drivers who operate VAA-equipped buses. In this way, it would be no different from the situation in agencies that have different bus models that require specific training to operate.

Reliability

Reliability is customarily measured in terms of the mean time between failures (MTBF) of infrastructure and onboard systems, subsystems, and components. Because VAA systems are relatively new and can be implemented using a number of different technologies, there is no universally-accepted standard. Each transit agency must develop its own guidelines based on current maintenance procedures, willingness to pay, and planned application. Whereas it may be technically possible to build a system that is virtually failure-free, after a certain point the marginal cost for each additional "unit" of reliability becomes prohibitive.

An example of the planned application's influence on setting reliability requirements is a segregated route using a single lane for both directions, which would require a higher level of reliability, as a disabled bus would block the entire system. Conversely, in a dedicated (but not segregated) bus lane, short headways would allow a bus to be taken out of service (and moved to the side of the road) with little effect on system performance, thus allowing for less demanding reliability standards.

Infrastructure reliability is generally dependent on an agency's choice of technology. The markers embedded in the road for magnetic guidance have a minimum chance to fail and are difficult to be blocked by surface obstacles,[3] whereas GPS is more subject to satellite blockage and signal interference.

Availability

Availability incorporates not only the reliability of the system (the probability that it will not suffer a failure), but also the time required to restore it to full operation. Availability is closely tied to system design, quality of routine maintenance, and system reliability. System design should allow for ease of checking and calibrating so that problems can be found before they become failures. One possibility for routine testing would be a short test track in the maintenance yard so that the tracking system of each bus could be checked as it leaves the yard to begin its daily run.

Again, design comes into play in the event of a failure in the field. It should be simple and fast to find and replace the faulty module so the bus can be placed back in service quickly. The ease and speed of repair combined with the quality of routine maintenance will determine the number of buses that need to be kept in reserve to maintain the desired level of service.

Infrastructure availability also should be taken into consideration. Will local weather conditions have an adverse effect, e.g., snow or ice on the guideway? In the case of a dedicated BRT lane, what effect will a crash on the adjacent traffic lanes have?

In the event of a guidance system failure, either onboard or with the infrastructure, that cannot be repaired, the system should be designed so the bus can operate manually, albeit at reduced speed.

Maintenance

A VAA system should be at least as durable as other onboard systems so the current service cycle can be maintained (for example, every 12,000 miles in the case of LTD). Suppliers of the systems should be required to modularize their system for ease of replacement, seal them sufficiently to withstand road hazards and bus cleaning, and equip them with a high level of self-diagnostic capabilities. The emphasis should be on a system designed with more modules rather than fewer. In this way, replacing a module that is beyond repair will be cheaper, pulling

[3]To affect the magnetic-sensing-based electronic guidance system, a sequence of magnets would need to be blocked with ferrous material. Such situations are relatively uncommon in real-world scenarios and would be relatively easy to detect.

and replacing by the maintenance staff will be easier, and spare modules will be more like commodity items than specialty items.

As buses have become more complex, the trend is to outsource more and more of the repair work, even in such "traditional" areas as engines and transmissions. The transit agency must decide which guidance system repairs will be carried out in-house and which will be sent out, although the modular "black box" nature of the system will favor the latter. The transit agency will define the average repair time after a failure occurs by the Mean Time to Restore (MTTR).

Currently, the service life of a bus is approximately 12 years. Given the current pace of changing technology, is it a reasonable expectation that a transit agency will want to continue with current guidance technology for the life of the bus? If the answer is yes, will replacement parts be available 10 or 15 years from now? Although the overall guidance system may be state-of-the-art, it should be constructed with proven, off-the-shelf components that reasonably can be expected to be around for a long time or a module that can be replaced with relative ease. Also, there should be assurance that future upgrades will be functionally backwards-compatible so the entire system will not have to be replaced.

Infrastructure Requirements and Modifications

The infrastructure modifications required for adoption of a VAA system depend on the type of operational venues, the selected technology, and the desired level of service features. Some examples of infrastructure needs are listed below.

- **Operation Scenarios or Applications**
  - Newly-created bus lanes on median –will require the construction of added lanes and dividers to use the median as dedicated bus lanes.
  - New division of existing roadways into special bus lanes – may involve re-striping of existing lanes into narrower paths or creation of a shoulder lane.
  - Narrow bridge or toll booth – will require minimum modifications on the bridge or at toll booths; however, there may be a need for changes of road markings or magnet installation to accommodate the lane guidance system for buses to pass through with electronic guidance functions.
  - Dedicated busways – to protect high-speed bus operations from other traffic on high-occupancy vehicle (HOV) lanes, corridors or special bus ways and some dividers or barriers may be needed.
  - Precision docking – to allow precision docking, stations or bus stops may need to be altered to allow the vehicles to dock closely to the platform so truly passenger-friendly, expedient alighting and boarding can be realized.

- **Technology Selection**
  - Vision-based guidance – uses cameras to capture images of the roadway as the basis for vehicle guidance and control; therefore, the striping or lane markings must be made conspicuous to the cameras.
  - Magnet-based guidance – involves the installation of magnets in the pavement, typically at intervals of 1 m or more.
  - GPS based guidance – does not require direct infrastructure modifications to the roadway, but differential stations and communication means may need to be set up to provide the appropriate differential information to the GPS receivers to obtain the desired accuracies.

VAA System Requirements

Based on the general considerations for system requirements and the VAA system functional block diagram described previously, detailed system requirements were developed. The top-level guidelines for VAA system requirements are as follows:

- The design and implementation of the VAA system shall not affect normal manual driving operations.
- The design and implementation of the VAA system shall not interfere with existing vehicle components mechanically, electronically, or electro-magnetically so the system will not imperil or degrade the performance of existing vehicle components and systems. For example, the electric power consumed by the VAA system shall be calculated carefully; if the consumed power is too large, a larger alternator may be needed to ensure smooth operation of the existing bus systems.
- The design and implementation of the VAA system shall tolerate normal wear and tear of any related or connected bus components.
- The implementation and application of the VAA system shall not jeopardize existing and new safety-critical operations.
- As a safety-critical system, the VAA system shall be designed to be fault-tolerant (capable of operating at the same or a reduced level of efficiency for a designated period of time after the failure of a component or power source).

Detailed VAA system requirements include safety requirements, performance requirements for individual functions, and technical specifications for subsystems. The safety requirements include hardware redundancy and requirements for fault detection and management. The performance requirements specify the requirements for VAA functions such as lane guidance, precision docking, lane-keeping, passenger ride quality, and HMI and driver interaction. The technical specifications include specifications for the vehicle position sensing subsystem, vehicle status sensing subsystem, steering actuator, and HMI system, as well as requirements for infrastructure, driver qualification and training, and maintenance. Collectively, these requirements and specifications define the operational conditions and environments and specify the performance, reliability, safety, and maintainability of the system.[4]

Safety Requirements

Since it is impossible to design a VAA system to be free of faults and failures, it is critical that it be designed to be fault-tolerant (capable of operating at the same or at a reduced level of efficiency for a designated period of time after the failure of a component or power source). Accordingly, the safety requirements include three dimensions: redundancy in system hardware, fault detection capability, and fault management capability.

Hardware Redundancy

It is essential that a VAA system have redundant hardware in all major subsystems and components, including vehicle position sensing, steering actuator, control computers, and HMI subsystems. The VAA system developed in the project addresses the hardware redundancy requirement as follows:

- Redundancy in vehicle position sensing – A VAA system (as described in Section 1) employs two sets of magnetometers (one at the front of the bus and the other in the middle of the bus) to provide redundancy in magnetic sensing. Vehicle and lane position sensing is critical for the operation of VAA-PD and VAA-VG systems. Therefore, redundant sensors shall be used to ensure safe operations. To satisfy this requirement, the prototype VAA system employs multiple layers of redundancy for vehicle position sensing. First, two sets of magnetometers (front and rear) are installed at two different locations under the bus. Second, within each magnetometer set, magnetometers are installed 0.2 m apart so that failure of an individual magnetometer can be accommodated by its adjacent magnetometer.
- Redundancy in steering actuator – Ideally, it would be preferred to have two steering actuators for actuating; however, due to resource and schedule limitations, the prototype VAA system used only one steering actuator for actuating. The driver is therefore served as a redundant steering actuator. As a result, the detection and management of faults in the steering actuator becomes critical and the driver is required to monitor the system operation and to override whenever the system does not operation as it should.
- Redundancy in control computers – Two control computers are included for redundancy purposes.
- Redundancy in HMI subsystems – Two HMI subsystems are used for redundancy purposes. Warning shall be provided as long as one of the two

[4]The reliability and availability requirements, as described in the general requirements described earlier, have been implicitly included in the safety and performance requirements; therefore, they are not listed as separate subsections.

HMI subsystems determines that a warning is necessary. Failure in a single HMI subsystem shall not prohibit interface between the driver and the control computers.

Fault Detection

Local Detection of Faults in Subsystems

- Fault detection for vehicle position sensing – Local fault detection shall be developed for each vehicle position sensing, steering actuation, and HMI mechanism. The fault detection for magnetic sensing shall be able to detect failures of individual magnetometers based on local signal processing, as well as failures of individual magnetic sensor bar.
  - The fault detection for DGPS/INS positioning shall detect failures in the DGPS receiver and INS (or IMU) sensors. In addition, the fault detection software module for DGPS/INS shall also monitor the operation of DGPS/INS to provide the quality of the positioning signal, including the availability of the GPS and Differential signals and the confidence level of the positioning accuracy.
- Fault detection for vehicle status sensing – Fault detection algorithms shall be developed to monitor the health of sensors that measure vehicle status including vehicle speed, yaw rate, and steering wheel angle, as well as the health of the communication data bus.
- Fault detection for steering actuator – All possible faults or failure modes in the steering actuator shall be determined, and the nature and potential consequences of these faults shall be investigated and understood. Detection algorithms shall be designed for each fault that either requires driver's take-over or causes the bus to deviate from the lane center beyond the performance requirements.
- Fault detection for HMI subsystems – Fault detection algorithms shall be designed to detect failures in HMI subsystems. Also, watchdog algorithms shall be designed to allow the HMI subsystems to monitor each other's health or to allow the control computers to monitor the health of each HMI subsystem.

Fault Detection in the VAA System

- Fault detection in the lower system level – The lower system level fault detection mainly works at the signal level to detect failures by comparing the consistency of similar signals from different sources.
  - The lower system level fault detection shall detect faults in vehicle position sensing by comparing the measurements from the different position sensing mechanisms. In the prototype VAA system, faults in vehicle position sensing shall be detected by comparing the measurements from the front magnetic sensor bar with those from the rear magnetic sensor bar.

  - Inconsistency in interfacing/communication shall be detected and analyzed to identify the failure.
  - Watchdog algorithms shall run on control computers to check each other's heartbeat for health monitoring, and the commands and outputs from each control computers shall be compared to detect any inconsistency.
- Fault detection in the upper system level – Software redundancy shall be built in the control software to facilitate the detection of failures in control software.

Fault Management

Hazard analysis shall be performed for each of the faults to understand the potential consequence of the failures. According to severity of the potential consequence, a three-level fault management strategy shall be implemented:

- Fault-tolerant operation – The VAA system is capable of tolerating the fault without noticeable impact on the system performance. For example, due to hardware redundancy, the VAA system will be able to tolerate failure in one HMI subsystem and continue functioning with the remaining functional HMI. In these cases, the system shall still provide warnings to indicate the fault.
- Degraded-mode operation – The VAA system is capable of maintaining the operation at a reduced level of efficiency. For example, if one magnetometer sensor bar fails, the VAA system can still perform lane-keeping functions with the remaining magnetometer sensor bar, although the accuracy may degrade. In such cases, the system shall provide warnings to notify the driver of the fault.
- Driver take-over required – In cases in which the VAA can no longer perform its desired functions or the performance degradation is unacceptable, driver take-over is expected. The system shall warn the driver as soon as such fault is detected. For example, critical failure of the steering actuator shall trigger warnings for the driver to take over the control.

The driver shall be trained and advised to monitor the performance of the VAA system once he or she activates the system. Furthermore, the driver is required to override or de-activate the system whenever the system does not operation as it should.

Performance Requirements

This section specifies the performance requirements for the VAA functions of precision docking, lane-keeping, passenger ride quality, and HMI and driver interaction. These performance requirements guide the determination of the technical specifications of VAA subsystems, which will be described later.

Precision Docking Performance

The performance requirements for precision docking address the following three aspects of the performance: docking accuracy, operational conditions, and manual-auto transition characteristics.

Docking Accuracy

The performance of precision docking is subject to legal performance requirements from the ADA, a complete review of which can be found at http://www.usdoj.gov/crt/ada/reg3a.html. In general, the horizontal gap between docking station and vehicle floor, measured when the vehicle is at rest, shall be no greater than 7.62 cm (3 in.), and the vertical gap between vehicle floor and station floor shall be within plus and minus 1.58 cm (5/8 in.).

In addition to the lateral stop accuracy (horizontal gap between docking station and vehicle floor), docking accuracy also includes longitudinal stop accuracy. The VAA system controls the lateral stop accuracy, and the driver controls the longitudinal stop accuracy within the accepted range to the desired stop locations. Therefore, the longitudinal stop accuracy is the responsibility of the driver in this VAA system.

Operating Conditions

The operating conditions shall include all environmental conditions encountered during normal transit operation with transition initiated by drivers.

Transition Characteristics

- Driver initiation and restriction – The driver can initiate the transition between manual and auto modes. However, if vehicle locations are within 0.2 m laterally and 5 m longitudinally of the platform, automated steering may not be activated if the VAA system has determined that the initial position of the bus is not appropriate for a safe docking maneuver.
- Transition time – The transition from manual to auto modes shall take no more than 0.5–1 seconds whenever the HMI indicates to the driver that the system is ready to engage, and the transition from auto to manual shall take no more than 0.15 seconds after the driver initiates a transition command.

Lane-keeping Performance

Similar to precision docking, the lane-keeping function shall satisfy performance requirements in the following three aspects: lane-keeping accuracy, operational conditions, and manual-auto transition characteristics.

Lane-keeping Accuracy

The lane-keeping accuracy requirement is determined by the lane width and vehicle geometry. For example, if a lane-keeping function is required for an 8.5-ft-wide (e.g., New Flyer 40-ft bus) bus riding on a 10-ft narrow lane, the maximum allowable deviation from the lane center is 0.75 ft (22.8cm). The lateral tracking error with respect to lane center shall be kept within 50–60% of the maximum allowable deviation (0.375–0.45 ft) for the whole speed operating range. It is worthwhile to note that the tracking accuracy described here does not include the necessary additional offset distance at the rear part or articulate part of the bus during turning due to the non-holonomic kinematic constraint. On turning segments, physical constraints require a wider lane than straight line segments—the sharper the curve, the wider the lane needs to be.

Operating Conditions

The operating conditions shall include all environmental conditions seen during normal transit operation, with transition initiated by drivers.

Transition Characteristics

- Driver initiation and restriction – The driver shall be allowed to initiate the transition between manual and auto modes when the system is ready to engage. The system shall be ready during most normal driving time along the guideway.
- Transition time – The transition from manual to auto modes shall take no more than 0.5–1 seconds whenever the HMI indicates to the driver that the system is ready to engage, and the transition from auto to manual shall take no more than 0.15 seconds.

Passenger Ride Quality Performance

To ensure a good ride quality, the lateral acceleration shall be no greater than 0.12 g more than the vehicle speed (m/s) squared divided by the curve radius (m) of the road, and the lateral jerk shall be no greater than 0.24 g/s for transit systems having only seated passengers [3].

HMI and Driver Interaction

The system shall provide feedback that a request has been received from a driver so that he/she knows that a request is being processed. The HMI shall have an update time of no greater than 200 m. When the system requires an action from the driver, it shall provide some preview information to the driver, such as through sounding a tone.

Technical Specifications of Subsystems

According to the system performance requirements, the subsystem (e.g., sensors and actuators etc.) requirements for VAA can be determined.

Vehicle Position Sensing Capability

Determine the vehicle's lateral deviation to lane center with high accuracy, high bandwidth and robustness is very important to the successful implementation of an electronic guidance/assist system. Measurement of the vehicle location may be achieved by one individual sensor or a combination of multiple sensors on the bus or be received from other sensors outside the bus through communications.

Spatial Coverage

Generally, spatial coverage shall cover the whole width of the desired operating roadway. The spatial coverage requirement can be smaller under certain operating scenarios. In the VAA project, a minimum range of 6 ft from the bus center was required.

Resolution

The position sensing resolution shall be better than ¼ of positioning accuracy requirements. For example, in the case of precision docking, the position sensor resolution shall be within 1–2 cm.

Robustness with Respect to Environmental Changes

The measurements of the vehicle position sensing system shall be consistent, regardless of changes in environmental factors. For example, it shall work similarly for road surfaces with/without snow and ice, rural roads with a clear view of the sky, urban environments with partially or totally blocked sky, and a clear view of road or foggy weather with low visibility.

Timing and Update Rate

The timing and update rate of sensors and signal processing shall be sufficient for achieving the performance requirements.

- Delay – The sensing time delay requirement depends on the vehicle dynamics and the final control system design. Although it is always preferable to have a sensing delay as short as possible, a rule of thumb requirement is that the sensing delay shall be small enough so the final control system satisfies the common 60-degree phase margin requirement. A typical necessary condition for the sensing delay is that the sensing dynamics shall be at least 5 times (preferably 10 times) faster than the vehicle dynamics. If the maximum operating speed is 60 mph (e.g., for lane-keeping), the vehicle dynamics is about 1–2 Hz; therefore, the sensing delay from input to output shall be shorter than 0.1 seconds to allow accurate tracking of bus dynamics at the 10 Hz update rate.

- Update rate – This requirement is similar to the time delay requirement. The update rate shall be at least 5 times (preferably 10 times) faster than the vehicle dynamics. For the maximum operating speed at 60 mph (e.g., for lane-keeping), the sensor data update rate shall be at least 10 Hz. The magnetic sensing subsystem shall support a data update sufficient to ensure no magnet update data are missing.
- Robustness to environmental factors – The measurements of the vehicle position sensing system shall be consistent, regardless of changes in environmental factors (e.g., heavy rain, standing water, snow, dirt, extreme temperature variations), or such factors shall be compensated.

Subject Vehicle Status Sensing Capability

Vehicle state information, such as bus motion state (steering angle, vehicle speed, yaw rate), bus operation state (door opening), and bus driver status (attentiveness, fatigue) can be integrated into the VAA system to improve either efficiency or safety. The following items specify the requirements for the subject vehicle sensors.

Vehicle Status Parameters

- Vehicle speed – Vehicle speed sensing shall encompass the full range of bus speeds. The maximum bus speed that the sensor can measure shall be at least 10 mph above the system maximum operating speed. The minimum bus speed that the sensor can measure shall be no greater than 1.5 mph (0.7 m/s). The minimum update rate shall be at least 10 Hz.
- Yaw rate – The maximum yaw rate that the sensor can measure shall be at least 150 deg/sec, and the minimum shall be no greater than 0.25 deg/sec. The resolution of the yaw rate sensor shall be better than 0.001 deg/sec.
- Steering wheel angle – The steering wheel angle sensor shall be able to measure the absolute position of the steering wheel. The sensing range shall be as wide as the maximum range (750 degrees for 40-ft New Flyer bus) of the steering system, with better than 1 degree accuracy.
- Data bus communication – Since an on-board J-bus or data network has become a primary trend for transit vehicles, the VAA system shall be equipped with capabilities to read and send (if required) data from the J-bus.
- Inertial navigation system (INS) – As a necessary backup for vehicle location sensing, it would be advantageous to equip the vehicle with INS (or part of a complete inertial measurement unit) so that dead reckoning could be executed to estimate the location of the vehicle between sensing samples or when other sensing functions are temporarily lost.

Events

Events relevant to VAA applications, such as door open/close, light on/off, etc., shall be converted into signals readable by on-board computers or transferable from the data bus. The transit operators will decide which of these events are required and needed to be converted in real time.

Steering Actuator

The steering actuator receives steering commands and turns the steering wheel to the desired angle according to these commands. It plays a vital role for lane-keeping and precision docking.

Steering Actuator Functions

The different steering actuator functional requirements for lane-keeping and precision docking operation are listed as follows:

- Operational mode – The steering actuator shall support the desired operational modes, which could include one or a combination of the position servo mode or torque mode.
- Position servo mode – When operating in the position servo mode, the steering actuator shall take the steering commands issued by the control computers and turn the steering wheel to the desired steering wheel angle according to the steering commands.
- Torque mode – When operating in the torque mode, the steering actuator shall accept the torque commands issued by the control computers and apply the desired torque to the steering wheel based on the torque commands.
- Smooth transition between manual and automatic mode – To enable transition between driver and automatic driving, the steering actuator shall have a transition function between manual and automatic mode.
- Self-calibration of zero steering angle – The steering actuator shall be able to calibrate the steering angle sensor and find the zero steering angle when the system starts.
- Fault detection and self-diagnosis – All failure modes of the steering actuator shall be identified and classified based on the impact of the faults. The steering actuator shall include self-diagnosis functions to detect both critical and non-critical faults and to provide the corresponding failure message to the control computers accordingly.
- Torque mode if haptic feedback is needed for HMI purpose – The steering actuator shall accept torque command if haptic feedback is needed. The steering actuator shall apply the corresponding resistive torque to the steering wheel based on the torque command to realize the haptic feedback to the driver.

Steering Actuator Performance Requirements

The steering actuator requirements shall be adequate for the resultant VAA system to achieve the desired performance requirements. Below are actuator functional requirements based on the system performance; these requirements guide the design of the interface requirements.

- Nonlinearity associated with steering mechanism – The original bus steering mechanism has various nonlinearities that may increase the difficulty of control system design for precision docking and lane-keeping functions. The free play shall be limited to no more than 10 degrees (steering wheel angle).
- Actuator power (rated torque) – The actuation force of the steering actuator can be generated electronically (by a motor) or hydraulically. The power of the steering actuator shall be large enough to overcome friction torque from vehicle tires in all anticipated circumstances, especially during low-speed situations such as precision docking. It is desirable that the power of the steering actuator be low enough so the driver could overcome it in the event of an emergency unless an appropriate override mechanism is included. For better steering actuator performance, the output force/torque shall be at least two or three times the largest resistant force/torque. The need to accommodate driver override torque may limit the severity of driving conditions under which the system can operate automatically (serious potholes, for example). A tentative requirement for the output torque is about 10 N-m at the steering column level.
- Actuator slew rate – The actuator shall be able to change the wheel position at least as fast as an experienced driver, so the maximum achievable slew rate shall reflect this. A starting point shall be 30 deg/sec at the tire or 540 degr/sec at the steering wheel.
- Servo performance – When the actuator works in the position servo mode, its steady state tracking error shall be within 1 degree at the steering wheel. The minimum position servo loop bandwidth shall be 4 Hz for small amplitude commands (within 20 degrees at the steering wheel). There shall be no observable oscillation and vibration on the steering wheel. When the actuator works in the torque servo mode, the steady-state error shall be less than 1 N-m at the steering wheel, and the torque servo loop bandwidth shall be at least 2 Hz.
- Transition performance – The transitions shall be "on-demand" whenever the system is ready. The following are recommended transition time limits: the transition from manual to automatic modes takes no more than 0.5–1 seconds, and the transition from automatic to manual takes no more than 0.15 seconds.
- Steering sensor accuracy – Steering angle sensor accuracy shall be within 1 degree at the steering wheel for the full steering wheel operating range (could be +/- 720 degree in steering wheel). Accuracy of 0.5 degree is

preferred for the steering servo controller design. If the steering actuator is designed to work in torque servo mode, steering torque sensors are required and their accuracy shall be better than 1.0 N-m at steering wheel.

- Steering angle and torque sensor redundancy – Redundancy is required for the steering angle sensor. The redundancy can be achieved by placing sensors using the same technology (e.g., two potentiometers) or sensors using different technologies (encoder and potentiometer).
- System calibration – To facilitate steering angle calibration, an absolute steering angle position sensor shall be installed. The zero steering angle calibration accuracy shall be within one or two degrees at the steering wheel.
- Fault detection and management – All system and component faults shall be detectable. No safety-critical faults shall be left without proper warning or failure management.
- Actuator redundancy – Steering actuator redundancy can be provided by multiple actuators of the same type or separate actuators using electrical and hydraulic power. They may be operated at the same time or one of them may only be used as an emergency backup. Due to resources and schedule limitations, only one steering actuator was used for actuating in the prototype VAA system. The driver, therefore, provided the redundant steering actuator function to the system. Critical failure of the steering actuator will trigger warnings for the driver to take over the control; furthermore, the driver is required to monitor the system operation and to override whenever the system does not operate as it should.

Human-Machine Interface System

The HMI shall inform the driver of system-relayed vehicle conditions (such as system ready, automation or manual state), system critical faults, and system responses to driver action or request. Furthermore, the HMI shall provide devices/means for the driver to make requests or select functions (such as activate and de-activate automation). The HMI subsystem shall satisfy the following performance requirements.

Interface Contents

- Vehicle to driver – The vehicle shall provide to the driver system-relayed vehicle conditions, system critical faults, and system response to driver action or request. The system-relayed vehicle conditions shall include system ready and automation or manual state.
- Driver to vehicle – The vehicle shall provide means for the driver to make requests or select functions (including activation and de-activation of automation); the vehicle shall also provide additional means for the driver to deactivate the system based on the specific operational scenario and safety consideration. Such additional means may include allowing the driver to take over the steering control by applying a noticeable torque on the steering

wheel, or a readily accessible kill switch. A steering torque shall be deemed as noticeable if it exceeds 10 Nm.

Processing Capability

- Delay – The processing delay from the processing computer to the interface unit shall be shorter than 0.1 s, and from the interface unit to the processing computer shall be shorter than 0.1 s.
- Update rate – The HMI update rate and delay shall not impact any driver operation or create safety critical situations. Therefore, the update rate shall be 10–20 Hz.

Redundancy

Since it is typically difficult to reliably identify certain HMI device's failure, redundant HMI subsystem shall be used for redundancy purposes. Warning shall be provided as long as one HMI subsystem warrants a critical warning.

Control Computer

Performance Requirement

The control computers are where the key software functional modules reside. The software functional modules include lateral controllers for the precision docking and lateral guidance functions, manual/automatic steering transitions, and fault detection and fault management. The performance requirements for the control computers that guide the interface design are listed as follows.

- Processor speed – The control computers shall have processors that are Pentium II equivalent or better, with math coprocessor.
- Interface requirement – The control computers shall have adequate hardware and software drivers to support the interfaces to other subsystems and sensors.
- Temperature range and cooling – The control computers shall be able to operate in temperatures ranging from -40 F to +185 F, with free convection cooling preferred.
- Enclosure – The enclosure shall have graded at least NEMA 3.[5]
- Redundancy – The control computers shall satisfy the redundancy requirement for enhanced safety.
- Maintainability – The equipment shall be designed insofar as possible to allow individual component replacement without damage to other components and packaging.

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[5]Enclosures constructed for either indoor or outdoor use must provide a degree of protection to personnel against incidental contact with the enclosed equipment and a degree of protection against falling dirt, rain, sleet, snow, and windblown dust and that will be undamaged by the external formation of ice on the enclosure.

Maintenance Interval Minimum Requirements

- The mileage interval between maintenance for the VAA system shall not exceed 6,000 miles.
- The time interval between maintenance for the VAA system shall not exceed 1 month.
- Routine diagnostics, including daily, weekly and monthly test procedures, shall be provided.

Infrastructure Requirements

Roadway Sensing and Construction

- Reference marker installation – The prototype VAA system employs magnetic reference systems as one of the sensing mechanism for vehicle position sensing; therefore, the requirements of magnetic marker installation shall be provided to the contractor. The magnetic marker shall be buried at a certain depth (variation shall be kept within 0.5 in.) with both lateral and longitudinal location within specifications, and perpendicular to road surface.
- Roadway and transit stop construction – These requirements are site-dependent and need to be planned in the deployment phase. Factors that affect these requirements include the curvature of the intended routes, vehicle type (e.g., articulated or non-articulated buses), and road tilt—the sharper the curves and the larger the road tilt, the wider the roadway needs to be, and articulated buses generally require the roadway to be wider than non-articulated buses. In general, the roadway shall be at least 25 cm wider than the width of the bus in straight-line sections and at least 35–50 cm wider in curvy sections depending on the radius of the curves and the vehicle type—the narrower the roadway, the higher the requirements on the road survey, the installation of the magnets, and the performance of magnetic sensing and the lane guidance control.
- Digital map.

Driver Qualification and Training Requirements

Driver Qualification

- Transit vehicle experience – The drivers of VAA-equipped buses shall have at least one year of transit vehicle driving experience based on the transit agency's qualification requirements as well as the operational complexity of the deployed VAA system.
- Training and evaluation tests – The drivers of VAA-equipped buses shall take both initial and follow-up training courses and pass evaluation tests to operate the VAA-equipped buses.

Training

- System training – System training shall cover issues related to overall VAA application, system operation, and fault management.
- HMI training – HMI training shall familiarize drivers with system responses, driver interaction, and emergency handling actions.

VAA Interface Requirements

The objective of the interface requirements is twofold: to ensure that the VAA system can interface seamlessly with the types of transit buses chosen for the VAA applications and to clearly identify and define the interfaces between VAA subsystems. Since interface designs are closely related to system designs and interface requirements need to support system requirements, the development of VAA interface requirements starts with the consideration of system design and system requirements.

Transit vehicles are manufactured primarily based on individual transit agency customized operational requirements. Although certain requirements are established industry-wide, most system or subsystem requirements of the vehicles are motivated by individual designs and component suppliers. As a result, the interfaces between VAA components and the mechanical, electrical, and electronic systems on the existing bus, if not defined properly, can be an impediment to the successful deployment of the VAA system. Therefore, understanding how the VAA system will interface with the existing bus systems and components of these two types of transit vehicles is very important.

Interface designs are closely tied with VAA system designs. For example, a "fully integrated approach" requires bus and VAA components to be designed interactively to achieve maximum integration, whereas an "add-on approach" designs VAA components to fit onto buses from different vendors with minimum modification of existing bus components. The Phileas bus developed by Advanced Public Transportation Systems (APTS) in the Netherlands is an example of a fully-integrated approach; its automated functions were designed in conjunction with the bus basic driving functions, thereby achieving maximum integration. A comparison of the integrated approach and the add-on approach is as follows.

- Fully integrated approach:
  - This approach enables the physical design and the performance of the basic bus driving functions to better meet the VAA needs; however, cost is extremely high and it is very difficult to adapt such VAA technologies to existing buses.
  - Problems can occur if the VAA functions are too closely coupled with conventional driving functions. A notable issue is that failures of the VAA components can affect the basic driving functions.

  - From the interface perspective, an integrated VAA system likely will not require standard interfaces for VAA components and newly-designed buses.
- Add-on approach:
  - Although less integrated than the integrated approach, this approach supports standalone components to fit onto existing buses and, therefore, likely could have wider applications.
  - From the interface perspective, it is important to have standard interfaces when VAA components and systems are add-ons to existing buses.
  - The interfaces would rely largely on existing bus designs and only specify necessary modifications of the existing systems to allow compatibility between the add-on components and the existing buses and infrastructure.

The prototype VAA system adopted the add-on design approach and was designed as an add-on system that is connected to existing vehicle subsystems. Due to the diversity of vehicle characteristics and the intense interactions between the VAA system and existing vehicle subsystems, it was essential to have information about the key components and subsystems of the transit buses that were used in this VAA project (as described in Section 1). The effects of the existing vehicle subsystem designs on the integration of VAA systems into buses were assessed to facilitate the determination of the appropriate interface requirements for the VAA system to work on the transit buses.

Although the interface requirements are not intended to directly address system level requirements, VAA interface requirements can impact or be impacted by VAA system requirements, either directly or through system designs. For example, a narrower bandwidth in-vehicle network could limit the update rate of the sensing and control systems, thereby negatively affecting the tracking accuracy of electronic guidance and longitudinal control systems. Therefore, VAA interface requirements need to be consistent and compatible with VAA system design and support VAA system requirements that specify performance, reliability, safety, and maintainability of the system. The assumption is made such that the VAA system would need to work with existing vehicle components; therefore, there is no need for redundant physical interfaces between the add-on VAA components and the existing components.

Detailed interface requirements were developed based on the characteristics of the existing bus systems and the system performance requirements, the. These interface requirements also were built on past experiences in lane-assist systems as well as the needs and requirements from AC Transit and LTD.

The prototype VAA system was implemented on an MCI 50-ft coach bus for the lateral control application on AC Transit's M Line and a New Flyer 60-ft diesel articulated bus for BRT lane-keeping and precision docking at bus stops on LTD's

Franklin EmX BRT route. However, the PATH team's goal is to design common vehicle interfaces for VAA subsystems to interact with a majority of existing buses. This preference establishes the foundation for a standard set of interface requirements that can be adopted by all manufacturers.

The interface requirements should clearly identify and define the interfaces among VAA subsystems. Based on the VAA functional blocks shown in Figure 1-1, the interactions between VAA subsystems and other bus subsystems can be streamlined. As a result, these interfaces can be defined to support all VAA performance requirements without becoming unnecessarily complicated or burdensome. Subsequently, the VAA interface requirements were developed based on the following design methodology:

- The interfaces are classified into three categories—mechanical interface, power supply, and data communication.
- Data communication is more challenging than the other two interface categories. The shared in-vehicle network was selected as the backbone of the modular system architecture.
- Because of the complexity of the VAA system, a "divide and conquer" design method was employed (i.e., the design was carried out for each VAA system functional block in each category). Emphasis was placed on important functional blocks such as vehicle and lane position sensing and steering actuation.

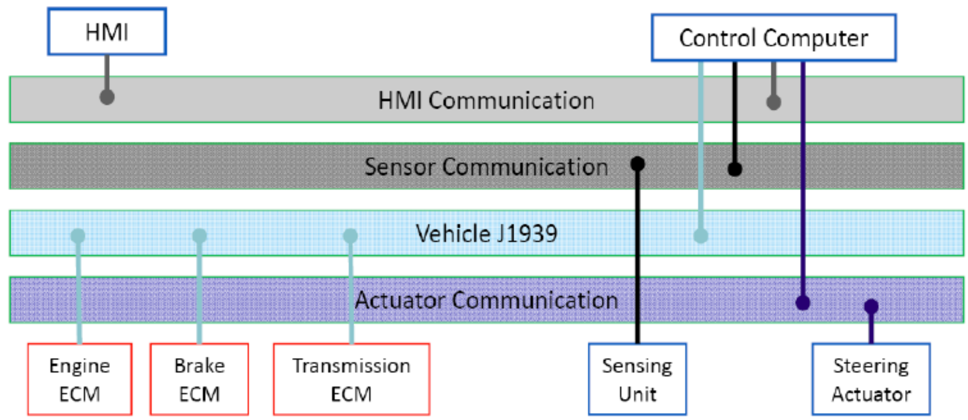
Three types of communication protocols are commonly used in a VAA system, including CAN, serial (e.g., RS232 and RS485), and Ethernet connections. After selecting the communication protocol, the interface requirements of the three categories (mechanical interface, power supply, and data communication) are provided for each of the following subsystems: vehicle position sensing, vehicle state sensing, steering actuator, HMI (including HMI processors and HMI devices), and control computers.

VAA Data Communication

Data communication can be implemented as point-to-point signal connections, a shared data network or various combinations of both types of communication. To ensure a simple, modular, expandable, upgradeable, reliable and redundant design for safety concerns, a shared data network approach is typically preferred. Figure 2-1 provides a schematic view of the VAA communication network, which shows the communication between the control computers and the following four major components: vehicle J1939 CAN bus (via a CAN bus gateway if necessary); sensing unit, including vehicle positioning sensors; steering actuator; and HMI subsystems.

Figure 2-1

Schematic for VAA communication network



In such a configuration, individual functional blocks such as sensors, actuators, HMI, and controller communicate via several data buses to form a distributed real-time control system. The data communication network subsystem functions as the backbone for the distributed system and becomes a critical component. From the multi-layered network Open System Interconnection (OSI) model point of view, the data communication network subsystem can be segmented into several different layers. The focus of this section is on the application layer, which addresses the following questions, the answers to which support the definition of the message framework as well as information interface requirements:

- What are the necessary messages exchanged among the different functional blocks of the VAA system?
- How often will these messages be exchanged?
- What is the priority of each message?

Different communication protocols were evaluated for distributed real-time control systems, especially for the safety-critical automotive applications such as X-by-wire (X = steering, braking, or throttle). Among them, CAN, serial (e.g., RS232 and RS485), and Ethernet communications are commonly used. The VAA system could employ a mixture of these three communication protocols.

CAN Communication Protocol

The CAN is a serial communications protocol that supports distributed real-time control applications with dependability requirements. CAN networks have the characteristic that the highest-priority message active on the network is always delivered, regardless of conflicting messages. CAN is popular in automotive electronics such as engine control modules, transmission control modules, and ABS with bit rates up to 1Mbits/s. The SAE J1939 protocol is a vehicle application layer built on top of the CAN protocol and is currently a widely-implemented standard for heavy-duty vehicles including the New Flyer 60-ft diesel articulated bus and the MCI 50-ft coach that are used in the prototype VAA applications.

A major drawback for CAN protocol implementation of distributed real-time systems is that it is event-triggered and requires careful analysis of the relative priorities and frequencies of all messages on the network to guarantee the timely delivery of messages required by real-time control systems. Future VAA systems may consider several different protocols (e.g., FlexRay, SAFEbus, Time Triggered CAN [TTCAN], Time-Triggered Protocol [TTP]) that have been proposed to add the time-triggered communication and other functions suited for real-time control systems. However, these communication protocols are not yet widely implemented in the heavy vehicle market.

Serial Communication Protocol

Serial communication protocols, such as RS-232 (Recommended Standard 232), RS-422, and RS485, are standard interfaces approved by the Electronic Industries Alliance (EIA) for connecting serial devices. Almost all modems conform to a serial communication protocol, and most personal computers have a serial port for connecting a modem or other device. The advantage of serial communication lies in its simplicity and flexibility in connecting two devices for data communication. A serial connection requires fewer interconnecting cables (e.g., wires/fibers) and, hence, occupies less space. The extra space allows for better isolation of the channel from its surroundings. In many cases, serial is a better option than parallel communication because it is cheaper to implement. In VAA applications, serial communication is often used to connect relatively simple commercial sensors (such as yaw rate, INS, or some GPS) to the control computers.

Message Types

In general, messages exchanged between different functional blocks can be classified into the following categories:

- Identification – Identification or source address is the unique signature for each electronic controller unit that sends the message. It could include component IDs not only for the components of different functional blocks but also for the components of the same type of functional blocks when redundancy is used to address reliability.
- Status – When a distributed real-time system configuration is used for safety-critical control functions, it is important that all the functional blocks connected together share a common view of the system state and use the same system state to compute outputs. To achieve synchronization among functional blocks, periodic message passing system and component status can be introduced. This status includes component status (e.g., ready/not ready and normal/fault) and operation status (e.g., acknowledgement of message receipt and the resulting status for certain operation such as calibration, control and manual/automatic transition).

- Command – Commands can be issued by certain functional blocks to other functional blocks such that certain operations will be performed or certain information will be provided.
- Health signal – A health signal is a specialized status message. It does not provide the sender's status directly. With such a signal, other functional blocks could diagnose the sender's status. It could be a heartbeat signal or a continuous counter embedded in a message.
- Data – Most of the traffic on the data communication network is data exchanged between functional blocks. It could be the sensor measuring results, parameters for certain functional blocks' operations, and commands.
- Redundant message – One way to improve system reliability of the data communication network is redundant message passing. The redundant message could be a simple replica of the original message or the original message with different encoding.

Message Properties

The following message properties need to be considered or determined in designing the messages exchanged between different functional blocks.

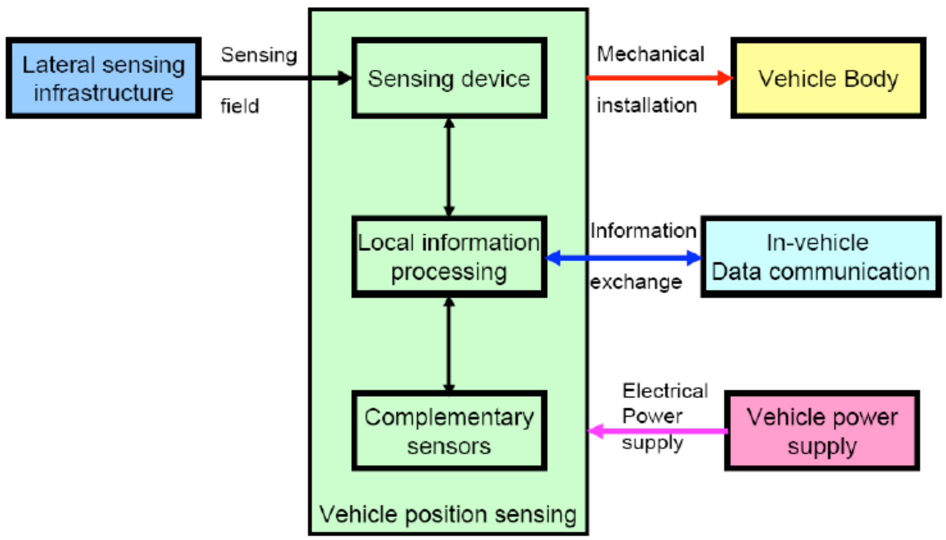
- Update method – Updates for sensor or status parameters can be broadcast on the network periodically or supplied only in response to queries from other functional blocks.
- Update frequency – The update frequency of a message is very important for real-time control. The frequency required is determined by vehicle dynamics and the desired control system performance.
- Priority – To ensure the timely receipt of the message, different priorities should be assigned to different messages. The principle is that messages related to the safety and with stringent timing requirements should have higher priority. But careful design must also ensure that the highest priority messages do not use up too much of the available data bus bandwidth with frequent updates and starve the delivery of other important messages.
- Message encoding and length – To ensure that the data exchanged among functional blocks has enough precision within its possible range, yet does not use any more of the communication bandwidth than necessary, numerical encodings such as fixed point limited range or integer case encoding of finite possibilities can be used. Short messages are preferred to avoid tying up the network in the case of other urgent communication. Error detection and correction coding is another way to ensure reliable message transmission.

Vehicle and Lane Position Sensing

Determining the vehicle's lateral deviation relative to the lane center with high accuracy, high bandwidth, and robustness is very important to the successful implementation of electronic guidance/assist systems. Figure 2-2 shows a general schematic of vehicle and lane positioning sensing. The sensing device, including the front and rear magnetometers and the GPS receiver, detects the changes or states (e.g., magnetic field or electro-magnetic wave) in the sensed infrastructure. The position between the vehicle and the lane is then resolved by local information processing of the sensor outputs and the result is sent to other functional blocks. Complementary sensors are needed for some technologies to ensure robustness and accuracy. For example, an INS sensor package is installed as a complementary sensor to a GPS system to mitigate GPS signal blockage situations. Furthermore, the front and rear magnetometers provide redundancy for each other to enhance fault tolerance in magnetometer failures.

Figure 2-2

Schematic for vehicle position sensing



Interface Requirements – Mechanical Installation

For the magnetic marker system, the sensing infrastructure includes magnets buried under the road surface in a specific pattern. The magnetometers sense the magnetic fields created by the magnets. The mechanical installation of the magnetic sensing system shall satisfy the following requirements:

- Since the strength of the magnetic field emitted by the magnets is limited by the available magnetic material, the magnetometers shall be installed close to the road surface and far away from potential interference by the vehicle's own magnetic fields.
- In some cases in which magnetic interference is unavoidable, magnetic shielding shall be designed to ensure the proper signal to noise ratio.
- When there are re-bars installed under the concrete road surface, smaller but stronger rare-earth magnets shall be chosen to avoid touching the re-bars.

For GPS systems, the sensing infrastructure includes the GPS satellites in addition to DGPS correction stations or subscribed/free services from Space Based Augmented System (SBAS) as well as digital maps of lanes. The GPS antenna receives radio waves from GPS satellites and DGPS stations (or satellites from SBAS). To ensure clear reception, the GPS antenna shall be mounted on top of the vehicle.

Interface Requirements – Electrical Power Supply

The vehicle position sensing systems generally do not consume much electrical power. Depending on the exact components chosen, DC-DC converters or DC-AC converters may be needed to interface with the existing vehicle electrical power system. The electrical power supply shall satisfy the following requirements:

- All safety critical subsystems shall accept 9~30 VDC from the vehicle batteries.
- Additional power regulation be included if the system module requires less noisy power inputs than the typical bus environment.
- Critical redundant systems shall have separate power inputs.

Furthermore, an uninterrupted power supply (UPS) or backup battery may be needed to provide a continuous power supply in case of main power supply system failure. Under such situations, a power control unit will also be included to detect the main power failure and to switch to the UPS upon the detection.

Interface Requirements – Data Communication from and to Magnetometer Unit

The messages from and to the vehicle position-sensing block, including the two magnetometer units and the DGPS/INS positioning system, are listed as follows:

- Sensor ID – The messages shall include a sensor ID, which gives a unique identification of the message origin for vehicle positioning sensing, especially when multiple redundant sensors are employed.
- Status – The messages shall include information indicating the status of the sensing block and the status of operation. The status of the sensing block shall include ready/not ready, normal/fault, and failure code. The status of operation shall include startup, shut-down, and calibration (if such a calibration operation exists). Status messages could use a slower update rate (e.g., below 1 Hz). Most status messages are important messages that need redundancy.
- Health – The messages shall include information indicating the health of the positioning-sensing units. The health information could be heart-beat signal or message counters embedded in the message.

- Lateral Position Outputs – The lateral position output message is a very important message for the VAA system: it is the sensing input for the lateral control system.
  - The lateral position message shall have an update rate greater than 10 Hz for speeds greater than 5 mph, and it shall have a high priority.
  - The message encoding provide enough precision over the possible data range.
  - The lateral position message shall be redundant for safety concerns. When multiple position sensing units are used, the lateral position message shall include lateral position outputs from each position sensing unit. In the prototype VAA system, the lateral position message shall include lateral position outputs from both the magnetometer units and the DGPS/INS unit.
    - For the magnetometer units, the measurements from the magnetometers shall be processed locally and two lateral position outputs shall be determined based on the front magnetometers and the rear magnetometers, respectively. It shall support an update rate sufficient enough to ensure no magnet update data are missing.
    - For the DGPS/INS unit, the vehicle position from the DGPS/INS integration shall be processed locally with the on-board digital map to generate a lateral position output.
- Confidence Parameter – The messages shall include a confidence parameter for each lateral position output. These confidence parameters provide information about how much trust can be placed in the corresponding lateral position outputs from the vehicle positioning sensing block. It could be a statistical parameter calculated by the vehicle positioning sensing block from its internal state, or an objective measure of the sensing environment (e.g., missed magnet indicator for magnet processing or ambient light meter reading for vision systems).
- Sensor Type – Sensor type indicates the exact sensing technology of the vehicle-positioning block. In the prototype VAA system, the messages from the two magnetometer units shall include a sensor type of magnetic marker, and the messages from the DGPS/INS unit shall include a sensor type indicating it is GPS.
- GPS Positioning Related Messages – Information directly from GPS such as speed-over-ground, GPS UTC time (Coordinated Universal Time) and the GPS status information (e.g., dilution of precision [DOP] and number of available satellites) shall be made available to the control computers through the communication between the GPS unit and the control computers. Other information obtained from digital map matching (e.g., road curvature, slope and distance to the next bus stop, etc.) shall also be available to the control computers.

- Magnet Sensing Related Messages – The magnetometer units shall also provide information such as position-sensing timing, magnetic polarities, coding and embedded information to the control computers. Alternatively, the coding information may be determined in the control computers based on the design decision.
- Calibration Parameters – Sensor calibration shall be performed when the system is started or upon request. The vehicle-positioning block shall provide calibration-related parameters, including sensor location and sensor range.
- System Command – System commands, including reset, calibration and change system parameters, shall also be included in the messages.

Vehicle State Sensing

The VAA system implements vehicle state sensing in two ways. First, it taps into the in-vehicle data network by connecting the two control computers with the existing vehicle J1939 CAN bus through a CAN gateway and a dedicated CAN bus. Engine and transmission electronic control units (ECUs) constantly broadcast engine/transmission states (e.g., vehicle speed, engine speed and gear position, etc.) over the vehicle J1939 CAN bus. This information then becomes available to the VAA control computers through the dedicated CAN. Second, an additional sensor, such as a yaw rate sensor, was installed to provide vehicle yaw rate measurement. The measurements are available to the control computers via connections such as a RS232 or RS485 connection. In addition, some information can be provided by other functional blocks of the VAA system through the corresponding dedicated data communication. For example, the steering angle is available from the steering actuator through a dedicated CAN between the control computers and the steering actuator, and additional motion information is available from the DGPS/INS unit (i.e., rotation rates and accelerations from the INS).

Interface Requirements – Mechanical Installation

To tap into existing in-vehicle networks such as J1939, the J1939 interface port shall be properly terminated and the connection wire length shall be limited within standard requirements to ensure good reception. The INS sensor such as the yaw rate gyro shall be installed away from local vibrating points, close to the vehicle center of gravity and firmly attached to the vehicle body.

Interface Requirements – Electrical Power Supply

Similar to the vehicle position sensing, vehicle state sensing does not consume much electrical power. Depending on the specific sensor selected, DC-DC converters or DC-AC converters, as well as power control units with backup power supply or UPS, shall be included to interface with the existing vehicle electrical power system. The electrical power supply shall satisfy the following requirements:

- All safety critical subsystems accept 9~30 VDC from the vehicle batteries.
- Additional power regulation shall be included if the system module requires less noisy power inputs than the typical bus environment.
- Critical redundant systems shall have separate power inputs.

Interface Requirements – Data Communication

The messages from and to the vehicle state sensing block are listed as follows:

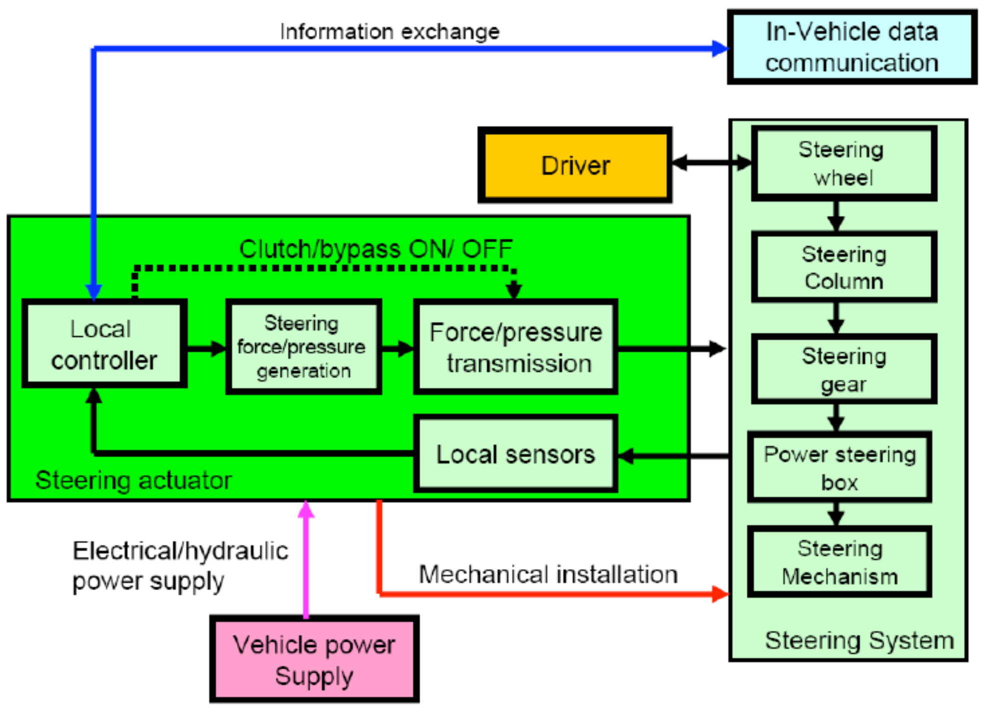
- Vehicle speed – Although the VAA system does not involve automated longitudinal control, vehicle speed is still important to the lateral control. Therefore, the message shall include vehicle speed and the update rate for vehicle speed shall be faster than 10 Hz. The message shall also have a high priority.
- Yaw rate – This is important to lateral control and the DGPS/INS integration positioning. Hence, the messages shall include vehicle yaw rate with high priority and the update rate shall be faster than 10 Hz.
- Lateral and longitudinal acceleration – Depending on the system design and control algorithm design, accelerometers for both longitudinal and lateral direction may or may not be needed.
- Engine/transmission states – Engine/transmission states, such as engine speed, engine torque, wheel speed, gear position, shift-in-progress, torque converter lock-up and retarder torque, are necessary for longitudinal control design. These signals can be obtained by tapping into the existing J1939 in-vehicle data networks. Generally, an update rate faster than 10 Hz is required. However, since the prototype VAA system does not include longitudinal control, most of these signals are not required. Engine speed and wheel speeds may be used as redundant data for the vehicle speed. If the lateral control state depends on the bus forward/backward state, the gear position, especially the reverse position, shall be available in the message. Low priority with update rate less than 1 Hz is acceptable for this message.
- Events – It is recommended (but not required) that the messages may also include events relevant to the VAA application, including door open/close, light on/off, wipers on/off and speed, and warning from collision warning system if available. The update delay shall be less than 0.1 sec for safety-related events and 1 sec for other events. However, none of these events are critical to the operation of the prototype VAA system. Events relating to the operational performance evaluation shall have higher priority for data conversion and storage.

Steering Actuator

Typically, the steering actuator can be an add-on device attached to the existing steering system, or part of a modified steering assist system. Figure 2-3 shows the schematic of a general steering actuation system. The steering force/pressure can be generated electronically by the electrical motor, hydraulically by the hydraulic valve, or mechanically by the contact between a guided wheel and guiding rail. Such steering force/pressure will be transmitted by a mechanism such as reduction gears or the hydraulic pipelines to the steering system. To ensure safe operation, unless the maximum torque of the steering actuator is small enough for the driver to overcome, a clutch or a hydraulic bypass mechanism, which can be controlled by the local controller or outside controller, shall be designed in the force/pressure transmission line to disengage the steering actuator when necessary. For modular system designs where the steering actuator functions as a position servo or velocity servo, the steering actuator shall also include components like a local processor which hosts local servo controller and local sensors for position or pressure sensing feedback.

Figure 2-3

Schematic of steering actuator



The prototype VAA system uses a steering actuator as an add-on device that consists of a DC motor for actuating the steering column. The following summarizes steering actuator implementation methods:

- Control system structures – Depending on the VAA system design, the steering actuator can work as a position servo, a torque servo, or a combination of the two. When the steering actuator functions as a position servo, the upper-level lateral controller (which resides in the control computers) sends a steering angle command to the steering actuator and the local servo loop inside the steering actuator actuates the steering system to generate the desired steering angle. This modular design structure decouples and simplifies the control system design. When functioning as a position servo, the steering actuator can also act as a torque generator based on the torque command sent by the control computer. Such torque command can be a function of lateral position as well as the steering wheel position.

- Torque generation methods – The steering actuator includes and uses an electric motor to generate the steering actuation. Compared to hydraulic power, the electric motor has the advantages of easy installation and a linear relationship between current input and output torque. Typically, a reduction gear system is needed to generate a large driving torque for the steering actuator based on a relatively smaller DC motor, especially when the motor is installed closer to the tires than the power steering box.
- Torque generation unit locations – When the steering actuator is located between the steering wheel and the power steering box (i.e., farther from the tire), a small torque generation unit is need. This allows the use of a relatively small motor and it is also easy for the driver to take over control when an emergency occurs or whenever the driver desires to. This installation needs minimal modifications to the original steering system. The steering actuator could be installed on the steering column or hidden in the bus between the universal joint and the power steering box. However, such a design includes existing steering system nonlinearities into the steering actuator design, and the installation space is still limited although the size of the motor is smaller.

Interface Requirements – Mechanical Installation

The mechanical installation shall satisfy space limitations and the steering actuator shall not interfere with the manual steering operations of the bus driver. The installation shall not create excess hard nonlinearities like friction and free-play, and the hard nonlinearities (free play, friction etc.) within the existing steering system be limited (less than 10 degrees at the steering wheel for the free-play is desirable) to facilitate VAA functionality.

In the prototype VAA system, the electric motor-based add-on steering actuator was installed on the steering column. Given the limited space on the steering column, the motor and its associated gear system shall be small enough not only to fit in the limited space but also to allow adequate space to ensure the driver can still comfortably drive the bus.

Interface Requirements – Electrical Power Supply

When an electric steering actuator is used, the vehicle shall be able to provide enough electrical power so that the steering actuator can generate the required force/torque for operation. For the add-on steering actuator design with an electric motor as the torque generation unit, large torque is still required for the electrical motor when vehicle speed is very slow (e.g., for the precision docking) even if a hydraulic steering assist is available. Since peak power demands can be large for the steering actuator in operation, attention shall also be paid to the effect of such a power surge on the remaining vehicle systems.

Interface Requirements – Data Communication

The messages from and to the steering actuator block shall include the following information:

- Actuator ID – Actuator ID shall give unique identification of the messages sent to/from the steering actuator.
- Actuator status – The actuator status shall include ready/not ready, startup/reset/calibration, normal/fault and failure code, which can be represented by integers. Actuator status messages could use a slow update rate (e.g., below 1 Hz when there is no status change) or variable rate (e.g., event-driven, updating whenever status changes). Most status messages are important messages that need redundancy.
- Actuator operation state – The actuator operation state shall reflect the current operating mode of the steering actuator, which can be represented by integers. It could be manual, automatic, or in transition. Actuator operation state could use a slow update rate (e.g., below 1 Hz) when there is no operation state change. Most actuator operation states are important messages that need redundancy.
- Actuator controller states – The actuator controller state shall reflect the current operation mode of the steering actuator controller, which can be represented by integers. The actuator control states could include position servo/velocity servo/torque servo mode, as well as the servo states (if applicable). Servo states typically refer to the levels of servo controller gain and that reflect how easy for the driver to override the system. Actuator controller states could use a slow update rate (e.g., below 1 Hz when there is no status change) or variable rate (e.g., event-driven, updating whenever status changes). Most actuator controller states are important messages that need redundancy.
- Health signal – A health message could be a heartbeat signal or a message counter embedded in the messages sent by the steering actuator.
- Actuator feedback states – Actuator feedback states are internal variables used by the local steering processor, which can be used for upper-level control or fault diagnostics and management. Although some of these feedback states may be updated with a much higher rate inside the actuator servo, the outputs used by the external system may be at a lower update rate. The messages from and to the steering actuator block could include the following actuator feedback states: steering angle, torque, servo error, and other internal variables.
  - Steering angle – Steering angles shall have accuracy better than 0.2 deg at the steering wheel, with an update rate at least 10 Hz.

  - Torque – Steering torque can be used for torque modes such as haptic feedback. The steering torque message shall have an update rate of at least 10 Hz.
  - Servo error – Servo error such as wheel position error or wheel velocity error can be used for upper-level control or fault diagnostics and management. The servo error messages shall have an update rate of at least 10 Hz.
  - Internal variables monitored – Some internal variables such as motor back electromagnetic fields (EMF) and hydraulic pressure can be used for fault diagnostics and management.
- Actuator mode command – The actuator mode command changes the operation mode of the steering actuator. It shall include manual/auto/transition and startup/reset/calibration that could be represented by integers. Update rate shall be at least 10 Hz. Actuator mode is an important command that shall need command redundancy.
- Actuator controller mode command – The actuator controller mode command changes the operation mode of the steering actuator controller. Dependent on the available servo functionalities, it may include position servo/velocity, servo/torque mode, and servo state, which could be represented by integers. Update rate shall be at least 10 Hz. The actuator controller mode command is an important command that shall need command redundancy.
- Actuator command – In the prototype VAA system, the electric steering actuator serves as a position servo; therefore, the actuator command is the steering angle position command. The actuator command shall have an update rate of at least 10 Hz, as well as a high priority and message redundancy for safety.

HMI (Human Machine Interface)

The VAA HMI may include switches, indication lights, or a display. The HMI installation shall be integrated with the existing driver control panel and be easy to see and reach.

Interface Requirements – Mechanical Installation

The mechanical installation shall satisfy space limitations and the HMI shall not interfere with the manual operations of the bus driver. Among the HMI devices, the switches for drivers to turn on or off shall be installed at locations easily reachable by the drivers, and the light-emitting diodes (LEDs) shall be at locations visible to the drivers. The sound devices are preferred to be installed close to the driver so as to limit their effect on the passengers.

Interface Requirements – Electrical Power Supply

The HMI subsystem does not consume much electrical power. Depending on the specific devices selected, DC-DC converters or DC-AC converters as well as power control units with backup power supply or UPS are included to interface with the existing vehicle electrical power system. The electrical power supply shall satisfy the following requirements:

- As a safety critical subsystem, the HMI subsystem shall accept 9~30 VDC from the vehicle batteries.
- Additional power regulation shall be included if the system module requires less noisy power inputs than the typical bus environment.
- Critical redundant systems shall have separate power inputs.

Interface Requirements – Data Communication

The messages from and to the HMI subsystem shall include the following information:

- HMI ID – HMI IDs shall give unique identification of the messages sent to/from the HMI modules.
- Lane assist status – The lane assist status shall indicate the operating status of the lane assist. For example, "system ready" indicates the lane assist function is ready to be turn on; "automated" indicates the lane assist function is turned on and active; "manual" indicates the bus operator is manually driving the bus; "fault" indicates the occurrence of a fault (or faults) in the VAA system.
- Driver action request – The HMI shall provide clear information and command to the driver whenever the system requires an action from the driver. The driver action request shall indicate whether an action is required from the driver, as well as the type of actions required. The action types could include information acknowledgement, manual takeover (with the request provided 2–5 seconds in advance) and emergency takeover.
- Driver requests – The HMI devices shall provide means for the driver to make requests or select functions such as activate and de-activate automation. For each type of driver request, a message shall be generated (by the HMI processors) upon the driver's input on the corresponding HMI device. The HMI processors shall report the message to the control computers, which determine and take the appropriate action accordingly.
- Driver request received – For each driver request, the system shall provide clear feedback to the driver whenever a request from the driver is received and processed. Upon receiving the message of driver request, the control computer shall generate a corresponding driver request received message if his/her request is received and executed. For example, when the drive activates the lane assist functions by pushing the activation button, the control computer receives the activation request from the HMI and activates the lane assist functions. The control computer then generates and sends the

HMI processor a request received message. The HMI processor may trigger a sound device to provide sound feedback indicating the request received; furthermore, the appropriate HMI device will be on to indicate that the lane assist status is "automated."

- System faults – All safety-critical faults of the system shall be detected and reported to the driver with proper warning or fault management. Therefore, fault messages shall include all safety-critical faults, including failure of both sets of magnetometers, critical failure in steering actuator, failure in two control computers, and failure in two HMI subsystems. These safety-critical faults require the driver to take over the control by switching off the system or overriding the steering. Non-critical faults of the system shall also be detectable and shall be reported to the driver, although driver action may not be required. Such faults include failure in individual magnetometers, failure of one set of magnetometers, failure in DGPS/INS positioning, failure in one control computer, and failure in one HMI subsystem. Failure messages shall also be created to indicate each type of these noncritical faults.
- Health – Health messages could be heartbeat signal or message counters embedded in the message. The health messages shall include all health messages from all critical processors connected with the HMI processors.

Control Computer

Interface Requirements – Mechanical Installation

The mechanical installation of the control computer shall satisfy the installation constraints of the selected space within the bus.

Interface Requirements – Electrical Power Supply

The controller module shall accept 9~30 VDC (preferably 8-30); the power supply shall work properly in the bus/vehicle environment.

Interface Requirements – Data Communication

The messages from and to the control computer are from other subsystems, such as vehicle position sensing subsystems, steering actuator, HMI, etc. Those messages have been defined in the data communication of those subsystems; therefore, they are not repeated here.

Infrastructure–Vehicle Interface Requirements

VAA systems involve interaction between vehicles and the infrastructure, so the interfaces between the vehicles and infrastructure are important to the successful design and implementation of VAA systems. Certain station/stop maneuvers, particularly the S-curve docking operation, may not bring the bus to a stop parallel to the platform due to the maneuver limitation of a bus or the physical space limitations of a station. Therefore, the platform may need to take a "non-traditional design" to accommodate the vehicle trajectory. Also, the design of the vehicle may impact the ability of the vehicle to access the station/stop, considering features such as the wheel lugs projecting, the door threshold projection, etc. It was preferred in this VAA project to minimize the modification to the existing infrastructure; therefore, the consideration on vehicle-infrastructure interactions mainly focuses on the infrastructure-based references. Typically, two primary aspects of infrastructure-vehicle interface need to be considered, including new or modified infrastructure design to take full advantage of VAA functionalities and infrastructure-based reference support for accurate and robust determination of vehicle position with respect to lane center.

Infrastructure/Vehicle Design

New infrastructure design or modifications to the traditional infrastructure design may be necessary to accommodate the requirements of VAA functions. The primary issues towards a VAA-oriented infrastructure design include:

- Running way – The main influence on running way design is focused on the running way width, which can potentially be reduced significantly below the standard lane width (12 ft for most cases). Other design factors for the running way such as pavement design and curve design are also discussed.
- Stations – Boarding platforms and entrance/exit profiles may have to be modified to accommodate the requirements of precision docking. The most important design elements for stations using precision docking include the vehicle floor height and boarding platform floor height need to be equal and the entrance/exit running way needs to be as straight as possible.
- Vehicle exterior geometry – Precision docking imposes design constraints on the vehicle exterior geometry compared with traditional bus body design, in order to enable the bus to approach the boarding platform very closely.

A detailed analysis of the interface requirements in the above three areas is provided in Reference 5. This project assumes minimum modifications to the existing infrastructure. Therefore, the interface requirements assume no modification in the design of existing running way, stations, and vehicle exterior geometry.

Infrastructure-based References

Determining the vehicle's lateral deviation relative to the lane center with high accuracy, high bandwidth, and robustness is important to the successful implementation of VAA systems. All lateral guidance technologies require the support of infrastructure-based reference information in one form or another. Examples of infrastructure references include specific lane marking or striping, magnetic markers, wires, mechanical guide, electronic map, or differential GPS signals. The sensor and the installation of the reference determine the accuracy of the lateral measurements. The "smoothness" of the road reference defined by such infrastructure significantly influences the ride quality when high tracking accuracy is required. In this VAA project, two VAA sensing technologies were used: magnetic marker sensing and DGPS/INS.

Magnet Reference System

A magnet sensing system uses magnetic material (e.g., magnetic tape or discrete markers) located on, or embedded in the lane center. In this project, discrete magnetic markers are used. The magnet reference system shall satisfy the following requirements.

- Magnets – The magnet sensing system can use both ceramic magnets and rare earth magnets. The magnet configuration for each magnet type shall provide similar magnetic strength at the designated sensor location under the bus.
  - Ceramic magnet – When ceramic magnets are used, four stacked disc magnets with 1 in. diameter and 1-in. height are recommended for each magnet sensing reference point. Thus, the total height is 4 in.
  - Rare earth magnet – Rare earth magnets are recommended to be used where dynamic loop coils, re-bars under concrete pavement are present, or other obstructions that might be buried in asphalt. Only one rare earth magnet is used for each magnet reference point due to the stronger field strength rare earth magnets have. That is, one disc with 1-in. diameter and 1-in. thickness is used for each magnet sensing reference point.
- Magnet track:
  - Location – The magnet track is recommended to be located within the center 60% area of the running way. For the prototype VAA system, it is located at the center of lane for the AC Transit's M Line, and it is at one side of the lane for the LTD's Franklin EmX BRT route.
  - Spacing – The spacing between two magnetic markers shall be large enough so that the interference from the other magnet marker is within noise range. It is recommended to be 1.0–1.5 m for the prototype VAA applications.
  - Diameter – The diameter of each magnetic marker hole shall be slightly larger than that of the magnets (1.0625 in. for ceramic magnet).
  - Depth – The depth of the magnetic markers holes is recommended to be at least ¼-in. deeper than the magnet (4.25 in. for ceramic magnet).
  - Orientation – The magnetic marker holes shall be perpendicular to the road surface.

  - Lateral accuracy – The maximum lateral error for the magnetic marker holes shall be less than 15% of the designated standard deviation of the tracking error. For the prototype VAA application, it is recommended to be 1 cm along station and 1.5 cm otherwise.
  - Longitudinal accuracy – The maximum longitudinal error shall be less than 20 cm. However, the recommended mean error is within 5 cm.
  - Magnets shall be installed no closer than 2 ft from dynamic loop counter coils
  - The magnet track shall avoid gaps between the concrete blocks and coils of the loop detectors on the roadway; therefore, the magnet longitudinal spacing shall be modified during the survey when such information becomes available. Also during survey, certain roadway marks, for example, location of the beginning of new roadway curvature should also be identified on the roadway.
- Polarity of magnets – It is recommended that the polarity of the magnets be changed in a pattern (binary code) in some segments of the magnet track to provide information to the vehicle about upcoming curves and the longitudinal location of the vehicle is on. The magnets shall be oriented in the holes in accordance with the polarity of a given code map.

GPS Reference System

For the AC Transit VAA applications, base stations were to be established close to the track, and the differential correction signal were to be broadcast through a proper radio link. A digital map was also to be a part of the sensing infrastructure for the GPS sensing system. The digital map should be detailed enough to provide the required accuracy and must allow access and map calculations to meet the real-time requirement.

- Base stations for lateral guidance – The location of the base station be optimized for the signal availability throughout the section of route which is equipped for vehicle lateral control. Repeaters are recommended to extend the coverage of the differential signals so that the whole section of VAA route is covered. The exact number of repeaters is determined by the condition of the site.
- WAAS differential signals for lateral guidance – Since WAAS are satellite-based, its differential signals are available to any WAAS-enabled GPS receiver without setting up any base station or repeaters. However, the accuracy of WAAS positions is much lower than that of a compatible GPS receiver whose differential signals are provided by a base station. The WAAS position is typically within 3 m accuracy, and the base-station-based DGPS position is typically within 0.5–1 m depending on the specifications of the selected GPS receiver.

- Digital map – When a VAA system requires cm-level accuracy in the DGPS-based lateral positions, the digital map shall have accuracy within 1–2 cm. When a VAA uses a WAAS-based DGPS, it has a much lower accuracy requirement for the DGPS positioning. Accordingly, the digital map for such applications shall have a lower accuracy of 0.5 m. Under such applications, the GPS-based sensing systems typically are used as a supportive sensing system rather than a primary sensing system.

SECTION

3

Development of Prototype VAA System

The development of VAA system is reported in this section. The current conditions of the two commercial transit buses are first discussed, followed by a summary description of VAA add-on components and testing conducted for component and system verifications. The work reported in this section involves to the three major milestones of the development phase of the VAA project: key components development, individual component testing, component integration testing and system validation testing.

Existing Bus Systems

The VAA system was designed as an add-on system connected to existing vehicle subsystems. The add-on system design introduced multiple interactions with existing vehicle subsystems, specifically:

- The VAA lateral control system interacts with the existing bus steering system, including its power steering, to perform the two VAA functions, lateral keeping and precision docking.
- The VAA system needs to take data from the existing vehicle data bus; the operation of the VAA system requires a variety of real-time information about the operation of the vehicle (e.g., speed, yaw rate, and steering angle, etc.). Some of this information is already measured and used by the existing vehicle subsystems (e.g., vehicle speed). Therefore, it is most efficient and cost-effective to acquire this information from the existing vehicle subsystems without adding new sensors.
- As an add-on system, the VAA system also has to draw power from the existing vehicle power supply and comply with the geometric space limitations imposed by the existing vehicle design.

Since transit buses are custom-built to meet the requirements of each individual transit agency, they represent a completely heterogeneous set of characteristics, especially in areas where there are no existing standards. Due to the diversity of vehicle characteristics and the intense interactions between the VAA system and existing vehicle subsystems, it is essential to gather information about the key components and subsystems of the transit buses that were used in this VAA project. The subsystems and components that affect the two VAA functionalities (i.e., lateral guidance and precision docking) include the physical shape and dimensions of the bus exterior and interior, steering mechanism, data network, and power systems. Field trips were made to transit agencies to gather information about existing bus subsystems. The effects of the existing vehicle subsystem designs on the integration of VAA systems into buses were assessed based on the information from the transit agencies (AC Transit and LTD), the experience with VAA technology implementation in prior PATH experimental projects, and inputs from transit agencies and bus manufacturers. This information is useful in determining the appropriate interface requirements for adapting the VAA technologies to work on the transit buses selected for the VAA project.

Existing Steering System

To keep a bus in a narrow lane or dock it precisely along a boarding platform, the steering actuator of the VAA system has to be able to steer the bus's front wheels to the desired angle using the vehicle's existing steering system. Therefore, the characteristics of vehicle's existing steering system are very important to the steering actuator design and implementation.

MCI 50-ft Coach

The project planned to equip one MCI 50-ft bus (Figure 3-1) with VAA technologies for the lane-keeping application on AC Transit's M coach Line. Figure 3-2 shows the steering wheel and steering column assembly on the MCI 50-ft coach bus. There was very limited space available for the addition of the steering actuator on the steering column, as shown in the figure. The steering actuator of the VAA system, including the necessary mounts and enclosures, must be compact enough to be able to fit in this very limited space. The design process, therefore, included carefully measuring and documenting all available space as well as possible mounting locations around the steering column. This information was then used in the hardware design of the steering actuator so as to ensure that the steering actuator was able to fit in the limited space. Props were made to facilitate the hardware design.

Figure 3-1

MCI 50-ft coach bus

Figure 3-2
MCI 50-ft coach bus steering wheel and column

New Flyer 60-ft Diesel

A New Flyer 60-ft diesel articulated bus, shown in Figure 3-3, was used equipped with VAA technologies for the lane-keeping and precision docking applications on the LTD Franklin EmX BRT route. Figure 3-4 shows the steering wheel and steering column assembly on the New Flyer bus. Similar to the case with the MCI 50-ft coach bus, there was very limited space available for the addition of the steering actuator on the steering column. Again, the design process included carefully measuring and documenting all available space as well as possible mounting locations around the steering column. The hardware design of the steering actuator was developed to be compact enough to fit in this very limited space.

Figure 3-3
New Flyer 60-ft diesel bus

Figure 3-4

New Flyer steering wheel and column (60-ft diesel)

The design efforts resulted in two different mechanical designs to accommodate the differences in the available spaces and the geometric limitations between the New Flyer bus and the MCI coach. The two pictures in Figure 3 4 illustrate the steering column on PATH New Flyer test bus before and after the steering actuator installation.

Power Steering System

Heavy-duty vehicles, including buses, typically use hydraulic power steering (HPS) to provide hydraulic power assist when the driver turns the steering wheel, thereby reducing the steering effort required of drivers. Therefore, the steering actuator design of the VAA system needed to take the characteristics of the power steering system into consideration.

Tests were performed to study the static characteristics of the power steering system on the New Flyer 60-ft diesel bus. A constant torque *M* was applied at the steering wheel to move the bus front wheels at a constant rotation while the bus was stopped on a paved road with the engine running. The steering torque of the power steering system was measured and the amplitude of the steering mechanism free-play was determined. Table 3-1 summarizes the test results for both the New Flyer 60-ft diesel bus and the 50-ft MCI coaches that were used the on the LTD Franklin EmX BRT route and AC Transit M Line.

Table 3-1

Power Steering System Test Results

	Steering Torque (Nm)	Free-play (Degrees at Steering Wheel)
New Flyer 60-ft Diesel Bus	10.6	<15
50-ft MCI Coach Bus	Between 10 and 12	<15

Existing CAN Bus

The CAN is a serial communication protocol that efficiently supports distributed real-time control with a high level of security. CAN provides a cost-effective communications bus for in-car electronics and as alternative to expensive and cumbersome wiring harnesses. Because of its proven reliability and robustness, CAN is now also being used in many other industrial control applications. CAN is an international standard and is documented in ISO 11898 (for high-speed applications) and ISO 11519 (for lower-speed applications)

CAN is a protocol for short messages. Each transmission can carry 0–8 bytes of data, which makes it suitable for transmission of trigger signals and measurement values. It is a Carrier Sense Multiple Access/Arbitration by Message Priority (CSMA/AMP) type of protocol. Thus, the protocol is message oriented, and each message has a specific priority according to which it gains access to the bus in case of simultaneous transmission. An ongoing transmission is never interrupted. Any node that wants to transmit a message waits until the bus is free and then starts to send the identifier of its message bit by bit. A 0 is dominant over a 1, and a node has lost the arbitration when it has written a 1 but reads a 0 on the bus. As soon as a node has lost the arbitration, it stops transmitting but continues reading the bus signals. When the bus is free again, the CAN Controller automatically makes a new attempt to transmit its message.

In the early 1990s, the Society of Automotive Engineers (SAE) Truck and Bus Control and Communications Subcommittee started the development of a CAN-based application profile for in-vehicle communication in heavy duty vehicles. In 1998, SAE published the J1939 set of specifications supporting SAE class A, B, and C communication functions. On modern trucks and buses, the engine, transmission, and braking systems are each controlled by separate Electronic Control Modules (ECM). These ECMs communicate via in-vehicle serial networks, typically using the SAE J1939 standard. These in-vehicle networks have several important functions:

- Broadcast – Information about engine speed, wheel speed, current gear, and many other vehicle system states is regularly broadcast by each ECM and may be used by other ECMs for control or for display of information.
- Command – The transmission or an anti-locking braking system may command or inhibit engine speed or torque by sending a message on these networks; advanced cruise-control systems may also use these capabilities. Commands can also be sent to activate airbrakes, transmission retarders, and engine retarders.
- Fault reporting – Special messages report faults and can activate dashboard “blink code” or error number systems for fault analysis.
- Off-line diagnostics and information reporting – The in-vehicle networks can be used for communication with a variety of service tools to report system

settings and trip information, and in some cases can be used to recalibrate the ECM.

The VAA system taps into the in-vehicle network to acquire sensor information that is already available on the network. Therefore, understanding the existing in-vehicle networks and integrating the existing in-vehicle networks into VAA systems simplified the VAA system design and saved the cost of additional sensors.

New Flyer 60-ft Diesel Bus

In the New Flyer 60-ft diesel bus, transmission, engine, and braking systems are all connected by both J1587 and J1939 networks. The New Flyer 60-ft diesel has a Detroit Diesel engine with an ECM that broadcasts on both J1587 and J1939 networks and also responds to J1939 Torque/ Speed Control command requests for engine torque and engine speed. No engine retarder is configured, and engine retarder messages sent to the engine ECM are ignored. The anti-lock braking system (ABS) on the 60-ft articulated bus is without the centralized electronic control of an electronically-controlled braking system (EBS). Thus, the brake system cannot be controlled via the J1939 network. The detailed J1939 network messages useful for VAA system design can be found in Appendix A.

MCI 50-ft Coach Bus

The MCI 50-ft coach bus has an in-vehicle communication network similar to that of the New Flyer 60-ft diesel bus. The vehicle speed is available on the J1939 network. The VAA system provides lateral control for the precision docking and lateral guidance functions; it does not provide automated longitudinal control. Therefore, engine speed and transmission speed may not be required, although they can still be used to support the lateral control. The minimum set of signals required from the existing J1939 CAN bus included vehicle speed, with 10Hz as the desired update rate. The minimum speed should be less than 1 mph (otherwise more complicated data processing is needed for speed estimation).

Electrical Power System

The vehicle electrical power system supplies electrical power to all vehicle subsystems and usually includes batteries, which are charged by an alternator driven by the engine. The electronic components of the VAA system need to draw power from vehicle's existing electrical power system. In order to minimize power supply complications in implementing the VAA system, it is preferred to use components that are already compatible with the standard onboard electrical power characteristics of transit buses.

New Flyer 60-ft Diesel Bus

The electrical system is a 12/24 VDC split system, negatively grounded—that is, all components are rated at 12 or 24 volts DC, depending on the system in which they are employed.

MCI 50-ft Coach Bus

The electrical system of the MCI 50-ft coach is also a 12/24 VDC split system, negatively grounded.

All power to system modules accept 9~30 VDC from the vehicle batteries; additional power regulation is included if the system module requires less noisy power inputs than the typical bus environment; critical redundant systems all have separate power inputs.

Key Components and Modules

This section discusses the component development in the development phase of the VAA project. The key components of the VAA system include the steering actuator, magnetic sensor modules, DGPS/INS module, control computers, and the HMI. Description of these key components and the corresponding software modules follow.

Steering Actuator

The steering actuator is an essential component that provides steering assist functions for performing lane-keeping and precision docking in this VAA project. Based on the technical specifications, the PATH team designed a prototype steering actuator and determined the actuator motor and relevant sensors. The basic subcomponents of the steering actuator include a steering column, a DC motor for actuating the steering column, a worm gear between the DC motor and the steering column, an angular position sensor for measuring the steering wheel position, an enclosure and mounting bracket for housing all those above components, and an embedded processor that obtains the steering angle positions from the angular position sensor, receives upper-level commands from the control computers, and provides lower-level servo commands to the DC motor.

The procedure for installation of steering actuator included 1) replacing the original steering column with the prototype steering actuator assembly; 2) powering the steering actuator, its ECU, and the embedded processor with the bus DC power sources; and 3) interfacing the embedded processor with the on-board control computers.

Magnetic Sensor Module

Magnetic sensor modules measure the lateral position of the VAA-equipped bus with respect to the magnetic track installed in the roadway. A magnetic sensor module consists of multiple magnetometers and a local embedded processor, a power module, and CAN communication controllers, as well as the associated custom enclosure with mounting brackets and connectors.

The magnetic sensor modules include the embedded system and the relevant software drivers. The magnetic sensor processing software module resides in the embedded system and is run by the embedded processor whenever the sensor module is powered on. Two magnetic sensor modules are mounted under the bus body frame. The embedded processor of the magnetic sensor modules were connected to the on-board control computers for data interfacing via CAN communications. The installation involved mounting the magnetic sensor modules beneath the bus frame, connecting the magnetic sensor modules to the bus DC power source, and interfacing its embedded processors to the on-board control computer.

DGPS/INS Module

Different GPS modules were used in the LTD and AC Transit applications. The LTD bus equipped with the VAA system has an on-board mid-range GPS module selected and installed by LTD. In this project, measurements from this mid-range GPS module were recorded, and off-line analysis was conducted to investigate its feasibility in serving as the lateral sensing for VAA applications.

The DGPS/INS module for the VAA applications at AC Transit provides a robust, accurate, tightly-coupled DGPS and INS integration. This module includes a DGPS base station and a DGPS/INS mobile unit, which further consists of one embedded computer, a dual-frequency GPS, an IMU, a 2.4 GHz communication modem, a power module, and the associated antennae, software, and custom enclosure with cables and connectors. A high-precision DGPS/INS module developed by University of California at Riverside was used as a second position sensing mechanism for lateral control. Similar to the magnetic sensing module, this DGPS/INS module provides estimates of a bus's lateral deviation from the lane centerline defined by the magnetic track. In this high-end DGPS/INS module, a high-end DGPS receiver with real time kinematics (RTK) capability was integrated with a six degrees of freedom (DOF) IMU to achieve highly accurate position measurements. This module is connected to one of the control computers. UC Riverside was responsible for developing this DGPS/INS module, including its DGPS/INS integration software module.

The communication (900MHz) and DGPS antennae were installed on the bus roof, with cabling properly connecting the DGPS/INS mobile unit to the bus DC power source and interfaced the processor of the DGPS/INS mobile unit to the on-board control computer. In addition, PATH staff, with the support of the University of California at Riverside, also set up a DGPS base station with 900MHz communication broadcast at the test site along SR 92.

The processor unit of the DGPS/INS mobile unit was mounted onto the test bus (on the bus roof and in the interior of the bus); the communication modem and GPS antennae were mounted onto the bus roof outside the bus. The DGPS/INS mobile unit was connected to the bus DC power supply, and the GPS antenna and the 2.4 GHz communication modem are powered by the DGPS/INS mobile unit. The embedded computer in the DGPS/INS mobile unit was also connected to the VAA control computer via serial port communication for data interfacing. The installation of the DGPS/INS module also included setting up a DGPS base station with 2.4 GHz communication broadcast.

Control Computer

For redundancy purposes, two control computers, each with its own separate power supply, are used in the VAA system to perform sensor fusion, lateral control, and fault detection and management. Serving as the brain of the VAA system, these two control computers host the key software functional modules and maintain the main data communication channels of the VAA system. Each control computer communicates with the steering actuator, magnetic sensor modules, DGPS/INS module, HMI, existing J1939 CAN networks in the bus, and the other control computer. Each control computer has a separate power supplier that is directly connected to the bus DC power source.

The installation of the control computers includes properly connecting two prototype control computers with two independent power control boards, interfacing two control computers with each other through CAN interfaces, and connecting the two control computers with other VAA system components (such as the steering actuator, magnetic sensor modules, and so on). The installation further includes connecting the two independent power boards to the bus DC power source.

On-board Communication Interfaces

Figure 2-1 provides a schematic view of the VAA communication network, which shows the communication between the control computers and the following four major components: the vehicle J1939 CAN bus (via the On-Board Diagnostic [OBD] CAN connector in the test bus), the sensing unit, the steering actuator, and the HMI subsystems. Data communication can be implemented as point-to-point signal connections, a shared data network or various combinations of both types of communication. To ensure a simple, modular, expandable, upgradeable, reliable and redundant design for safety concerns, the VAA system takes a shared data network approach and chooses CAN communication for the communication between key components.

The VAA system taps into the in-vehicle data network by connecting the control computers with the existing vehicle J1939 CAN port of the test buses with proper wiring, shielding, and termination. ECUs constantly broadcast engine/transmission states (e.g., vehicle speed, engine speed, gear position, etc.) over the vehicle J1939 CAN bus. This information then becomes available to the VAA control computers through the dedicated CAN. For the VAA project, the existing CAN port was connected to the off-the-shelf CAN interface controller board that is resided within the control computers. The CAN interface controller is powered through the control computer which is connected to the bus DC power source.

HMI Module

The HMI module provides information to and receives commands from the bus operator, receives system operating status from and sends the operator's command to the control computers, and monitors the integrity of the information and system operation. It was developed with redundant audio and visual feedback to the driver and is connected to both control computers for redundancy.

Figure 3-5 and Figure 3-6 show the VAA system components on the LTD New Flyer bus and the AC Transit MCI coach, respectively. The key components include the steering actuator, magnetic sensor modules, control computers, and HMI module. This section focuses on the driver interface and the HMI module. In addition to providing the interface with the bus operator under both normal and fault conditions, the HMI module serves as an arbitrator when there is any command inconsistency between the two control computers. Since the HMI module and the control computers share a CAN, the HMI module also receives data communicated between the two control computers; therefore, it also serves as another layer of fault detection and management devices for the VAA system.

Figure 3-5

Driver VAA interface components for LTD New Flyer 60-ft articulated bus

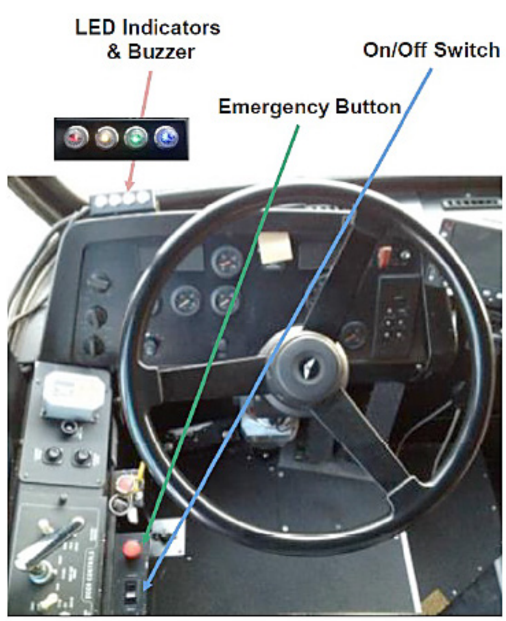
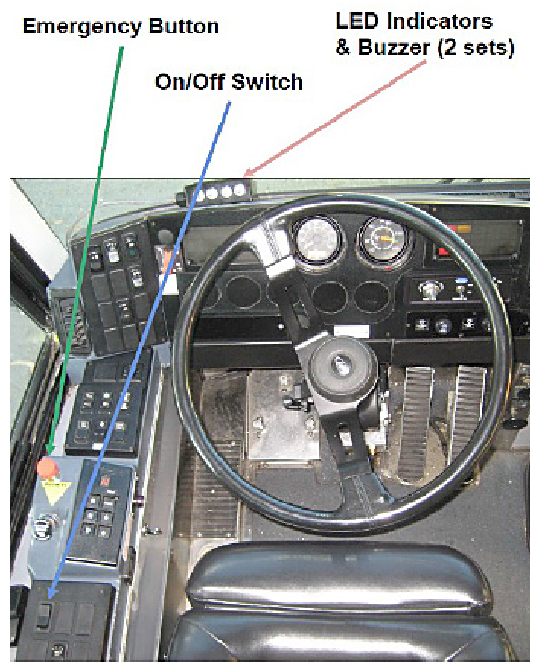


Figure 3-6

Driver VAA interface components for AC Transit MCI coach bus



Accordingly, the HMI module includes two embedded systems with independent power supplies and two sets of input wires, LEDs, and buzzers. Each set is controlled by one HMI processor and runs independently of the other set. The driver interfaces with the VAA system through the following driver interface components (devices), as shown in Figure 3-5 and Figure 3-6: LED indicators, buzzers, switches/buttons, and the steering wheel.

LED Indicators

As shown in Figure 3-5 and Figure 3-6, LEDs with four different colors (amber, green, blue, red) were installed on top of the bus dashboard. Each color consists of two identical LEDs, and each LED is controlled independently by one HMI processor. The main purpose of the LEDs is for the VAA system to have a simple and direct way to tell the driver about four main states of the VAA system: 1) system on or off, 2) auto function ready or not, 3) auto function engaged or not, and 4) any fault detected or not. The meanings of the LEDs as well as the corresponding blinking patterns are explained as follows.

- Amber LED – Primarily provides indication of whether the VAA system is on or not.
  - Solid on – VAA system has booted up; it is functioning without fault but not ready for automation yet.
  - Solid off – VAA system is off (if all LEDs are off), or ready for automation (if green LED is on), or faulty (if red LED is on).
  - Flashing – VAA system is in the stage of booting up.

- Green LED – Indicates to the driver that the VAA system has detected the magnet track and the automated function can be activated at any time. The patterns and their associated meanings are as follows:
  - Solid on – VAA system's automatic function is ready for activation (AUTO READY).
  - Solid off – VAA system's automatic function is not ready for activation; it typically means that the system has not detected the installed magnets.
- Blue LED – Indicates to the driver that the VAA system's automatic steering function is engaged or not. The patterns and the meanings are as follows:
  - Solid on – The bus is under automatic steering control (AUTO ENGAGED).
  - Solid off – The bus is not under automatic steering control
- Red LED – Indicates the VAA system is faulty or not. The patterns and the meanings are as follows:
  - Solid on – At least one fault is detected by the VAA fault detection algorithms. The most likely situation is that such a fault is detected by the VAA self-diagnosis when the bus is not under automatic control.
  - Solid off – No fault is detected by the VAA system.
  - Flashing – At least one fault is detected when the bus is under VAA system automatic control. As it will be explained below, the buzzer will also sound whenever driver's response is requested.

Buzzers

The main purpose of the buzzers is for the VAA system to have a simple means to immediately inform the driver and obtain the driver's attention when needed. The meanings of buzzer's sound patterns are explained as follows:

- One short beep – Indicates an acknowledgement for any driver input such as activating or deactivating the automatic control function. A short beep will also sound at the time when the bus is first entering the magnetic corridor.
- Low-frequency continuous beeps – The buzzers generate loud beeps whenever a fault that requires driver's attention is detected during the VAA automatic control; the red LED flashes at the same time. The frequency of the beeping indicates the urgency of the requested driver response. The low-frequency beeping, tells the driver that: 1) a fault is detected during VAA automatic control, 2) the VAA system is currently handling such fault, and 3) driver should start preparing to take over the steering control function.
- High-frequency continuous beeps – A fast beeping from the buzzers means that the driver need to take over control immediately. The VAA system will also de-activate the VAA control function under such emergency conditions. Slow to fast beeping provides an instinctive indication to the driver of the urgency of the "taking over control" request.

Switches and Buttons

As shown in Figure 3 5 and Figure 3 6, one toggle switch and one push-down button were installed to the left side of the driver. The switch and button provide the driver a simple means to give his/her command to the VAA system. The usages of the switch and button are explained as follows:

- AUTO/MANUAL switch – The driver simply pushes the 2-position toggle switch (AUTO/MANUAL) to activate and deactivate the VAA automatic control function.
- Emergency button – When the emergency button is pushed down, the power to the steering actuator motor is disconnected, rendering the motor powerless. The driver thus has full control of the steering wheel regardless of how the VAA controller is commanding the actuator. Fault will also be reported.

Steering Wheel

The steering wheel itself is also a means for the driver to interface with the VAA system. Similar to a cruise-control system that can be deactivated when the driver presses down the brake paddle, the VAA automatic control function can be overridden (deactivated) when the driver provides torque to the steering wheel anytime during automation. As described earlier, a short beep will notify the driver when such an override occurs.

HMI Processor Module

The HMI processor module is a device that provides information to and receives commands from the bus operator, sends the operator's command to and receives system operating status from the control computers, and at the same time monitors the integrity of the information and system operation. The HMI module further consists of an embedded processor, power modules, digital I/Os, CAN communication interfaces, the associated custom enclosure with mounting brackets and connectors, LED lights, and switches. The HMI module is directly connected to the bus DC power supply, and the processor is connected to the control computers for data interfacing. The HMI module is powered by the bus DC power source, and is connected to the control computer for data interfacing.

Software Architecture

The VAA system software consists of software modules residing in each of the five key components. The magnetic sensor software module estimates vehicle position based on magnetic sensing, while the DGPS/INS software module provides position estimates by integrating DGPS/INS. The steering actuator servo software executes servo control to turn the steering wheel commanded by the control computer. The HMI software module is the interface between the driver and the VAA system. The software in the control computer implements the lateral controls and performs the precision docking and lane-keeping functions.

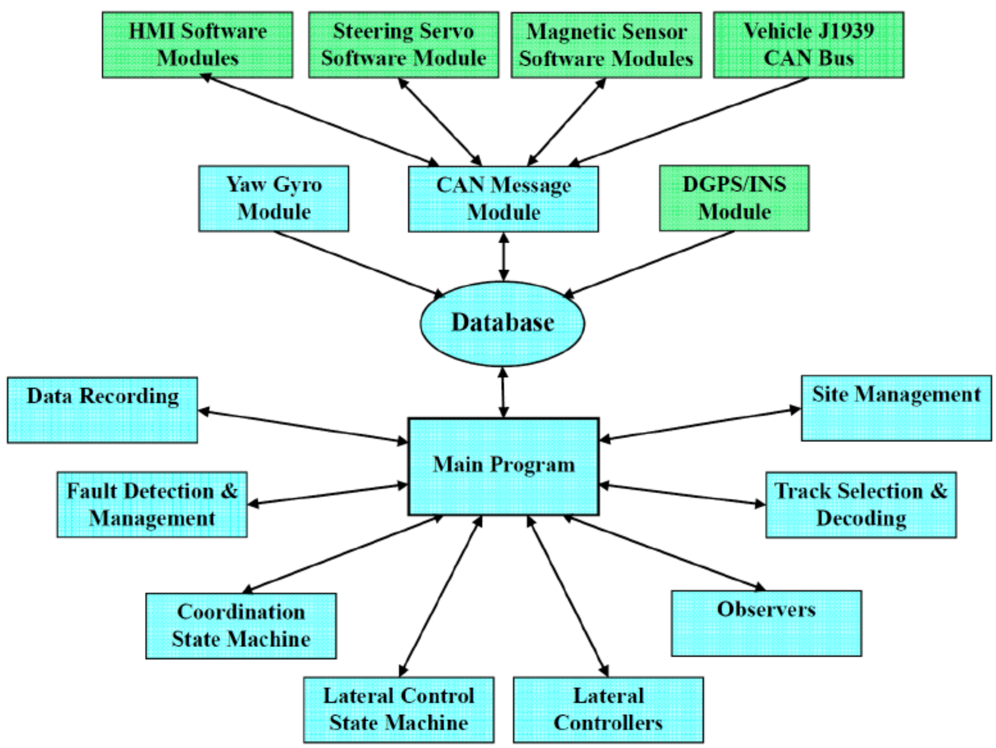
The software drivers and modules, together with the hardware components, were first implemented in an existing New Flyer bus at PATH, which served as the initial test platform for the VAA system. The initial debugging of the software drivers and modules (as well as the hardware components) was conducted at the PATH test track at RFS. The component integration included installation and functional evaluations of the software operating environment, firmware, software drivers, sensor calibrations, debugging and development tools, and data communications. After testing on PATH's 40-ft New Flyer bus, the verified VAA components were migrated to the VAA test buses from LTD and AC Transit.

Control Computer Software Module

Figure 3-7 shows the overall software architecture of the VAA system. The modules shaded in blue reside in the control computers,[6] and modules in green reside in individual components. The control computers communicate with the HMI module, the magnetic sensor module, the steering actuator module, and the vehicle J1939 CAN Bus through CAN communications. Both the DGPS/INS module and the gyro module communicate with the control computers via serial port communications. The low-level drivers (i.e., CAN drivers and serial port drivers) are not included in the figure for simplicity.

Figure 3-7

VAA system software architecture



[6]Note that the two control computers have the same software components; each control computer executes its software independently.

The database serves as a data hub for the various subroutines in the control computers. Variables from the CAN messages and serial port communications are received and updated to the database. The main program in the control computer obtains those variables and makes them available to all other subroutines to perform their corresponding computation and decision making; the main program also updates the database with the processed information and commands from the subroutines. Those processed information and commands are then communicated to the VAA components via CAN communications.

The main program (in the control computer) coordinates all the subroutines in the control computer. It reads the database to obtain inputs from all other VAA components and writes to the database the processed variables; it also calls all the other subroutines in the control computer so as to perform various VAA functions.

CAN is a message-based protocol, designed specifically for automotive applications but now also used in other areas such as industrial automation and medical equipment. The CAN messages sent or received via the CAN communications follow standard frame formats, which consist of a 64-bit data field for the data to be transmitted. The CAN message module consists of subroutines for packing the information from the control computers into CAN messages and for unpacking CAN messages received by the control computers into variables that are updated to the database and used by the subroutines in the control computer.

The site management module consists of subroutines that manage the information for different sites. Three sites are included in this VAA project: the test track at RFS, the EmX track of LTD at Eugene, and the HOV lane on SR 92 and through the San Mateo Bridge toll plaza. The subroutines in the site management module maintain and provide the site-specific information.

The track selection subroutines determine the magnetic track to be followed based on the site management module. The decoding subroutines decipher codes based on the polarity reported by the magnetic sensor bars, thereby determining the current location of the bus.

In VAA lateral control, observers are used to estimate variables that are not directly measurable or to improve the quality of the measurements. The observer subroutines are used in this VAA system to estimate vehicle lateral position at the locations at the control point used in the controller (for example, bus center of gravity).

The lateral controllers implement the control algorithms that determine the desired steering angle needed to perform the lateral keeping and precision docking functions. The control algorithms can be regarded as functions whose inputs are the estimates from the observers and the output is the desired steering angle, which is sent to the steering actuator as the steering command.

The lateral control state machine is a supervisor of the lateral controllers. It represents different stages for lateral control and activates different controllers to maintain and extend the performance envelop when faults are detected.

The coordination state machine is the top-level state machine in the control computer to control the state of the system. It initiates and controls the transition to automatic control upon receiving command from the HMI (when driver pushes the on switch), exits automatic control when driver override is detected or upon receiving commands from the HMI, and enters fault or emergency states when failures are detected.

The fault detection and management subroutines monitor the performance of various aspects of the system components to detect failures promptly and to take appropriate actions to minimize the effects of the failures. In addition, each key component (including steering actuator, magnetic sensor modules, HMI modules, and DGPS/INS module) has its own fault detection that closely monitors its own performance, detects and reports (to the control computers) faults in the corresponding component, and switch to degraded modes if available. The fault management subroutines handles both the faults detected by the control computer but also the faults reported by other components. The control computer reports the fault severity level to the HMI modules and the HMI modules notify the driver through a red LED and sound buzzer accordingly.

The data recording subroutine saves the specified variables to data files in the hard disk of the control computer. The data saved was used to analyze the performance of the prevision docking and lane-keeping as well as to support evaluation of the cost and benefits of the VAA system.

The low-level drivers are not included in Figure 3 7 to keep the figure simple and easy to understand. The low-level drivers implemented in the control computer include CAN drivers, serial port drivers, and Ethernet port drivers to support interfaces among various components.

Steering Actuator Software Module

The steering actuator executes the automated steering functions based on the steering command from the control computers. The steering actuator assembly mainly consists of a steering column, a DC motor for actuating the steering column, a worm gear between the DC motor and the steering column, an angular position sensor for measuring the steering wheel position, an enclosure and mounting bracket for housing all of the above components, and an embedded system for running the actuator servo software.

The core function of the servo software is to perform the servo control of the DC motor according to the steering angle command from the control computers. Since the control mode of the motor used in the steering actuator is torque control, the goal of the servo control is to determine the desired torque such that the steering column will be turned promptly and smoothly to the desired steering angle commanded by the lateral controller. To perform this core function, the actuator servo control includes the following subroutines: sensor processing, servo controllers, and low-level drivers.

The sensor processing subroutines process raw measurements from angle sensors (a potentiometer and an encoder inside the motor) to provide estimate of the rotation angle of the steering column. The servo controllers are basically the control algorithms that are used to compute the torque command based on the steering command from the lateral control (in the control computers) and the steering angle estimates. The low-level drivers include digital and analog IO drivers that are implemented to receive the raw measurements from the potentiometer and the encoder. A serial port driver is also implemented for sending the torque command to the motor as well as receiving motor status reported from the motor via a serial port.

To supervise, monitor, and support the core servo function, the servo software also includes actuator state machine, fault detection and management, and CAN interface and CAN drivers. The actuator state machine reflects the states the actuator is in and run the servo controller accordingly. The fault detection and management subroutine monitors the health of the actuator, and the faults detected will be reported to the control computer via the CAN communication. The CAN interface subroutine packs the variables that need to be sent to the control computers into the standard format and unpacks the CAN messages received from the control computers into variables to be used by the actuator software. The CAN drivers are the low-level driver that actually handles the sending and receiving of the CAN messages.

Magnetometer Sensor Software Module

The magnetometer sensor software module resides in the embedded system inside the magnetometer sensor modules. It collects measurements of the magnetic field strength from the magnetometer sensors, processes these strength measurements to estimate the lateral position of the bus relative to the magnetic track, and to report the position estimates to the control computers.

The magnetometer sensor software module includes the following subroutines: sensor signal pre-processing, the lateral position estimation, fault detection and management, CAN interface and CAN drivers, and low-level drivers. The sensor signal pre-processing obtains the raw measurements and filters the measurement noises. With the filtered signals as inputs, the lateral position estimation tracks the changes in magnetic field strength around each sensor and estimates the lateral position of the bus relative to the magnetic track accordingly.

The fault detection and management subroutine monitors the health of each magnetic sensor and low-level drivers. It evaluates the sensor measurements to detect faults in sensors and monitors the receiving and sending of the CAN messages to detect CAN driver failures. The faults detected are then reported to the control computer via the CAN communication. The CAN interface subroutine packs the variables that need to be sent to the control computers into the standard CAN message format and unpacks the CAN messages received from the control computers into variables to be used by the magnetic sensor software. The CAN drivers are the low-level driver that actually handles the sending and receiving of the CAN messages. The low-level drivers also include software driver that read sensor raw measurements.

DGPS/INS Integration Software Module

The DGPS/INS integration software module described in this section is developed by University of California at Riverside and it is used in the AC Transit application only. (As described earlier, the DGPS module on-board LTD bus is a commercial off-the-shelf DGPS system selected and installed by LTD.) The differential global navigation satellite system (GNSS) aided INS includes the following hardware components: a Novatel GNSS receiver and antenna that provides GPS pseudorange and carrier phase measurements at 1 Hz, an inertial measurement unit (IMU) that provides angular rate and specific force measurements at 200 Hz, an ATT USB modem that communicates differential corrections from a remote base station to the equipment on the bus.

The DGPS/INS integration software module processes the pseudo-range measurements from GPS receivers and the differential signals broadcasted from the differential stations, and then integrates them with IMU measurements to provide position estimates with up to centimeter-level accuracy. The DGPS/INS integrated software module includes the following subroutines: vehicle state prediction, GPS error prediction, extended Kalman Filter (EKF), and map integration. The vehicle state prediction subroutine integrates the IMU measurements through the vehicle kinematic model to predict the vehicle state vector; it also takes the INS error state estimated by the EKF as an input to reduce the effects of INS bias and noises on the integration. The GPS error prediction subroutine uses the vehicle state vector to predict the GPS pseudorange and carrier phase and then compute the prediction error between the predicted values and the measurements from DGPS. The prediction error is then input to the EKF, which estimates the INS error state and calibration factors both for the IMU and GPS. The map integration subroutine further processes the vehicle state relative to a map of the lane trajectory to compute the control state vector. The control state vector (including the vehicle lateral position relative to the magnetic track) is then output to the control computers via serial port communication. Rigorous discussion of the detailed software of the DGPS/INS integration can be found in Reference 7.

HMI Software Module

The HMI module in the VAA system consists of an embedded system and a driver interface that consists of LEDs, sound buzzers, and switches for drivers to operate the system. The HMI software module resides in the embedded system and runs automatically when the embedded system is powered on.

The core function of the HMI module is to receive and process driver's inputs and to inform driver of the system operational and health status; therefore, the HMI software module consists of the input handling subroutine, the device control subroutine, and the HMI state machine. To support its core function, the HMI software module further includes fault detection and management, CAN interface and CAN drivers, low-level drivers.

The driver input handling subroutine reads the switch inputs from the digital IOs, filter the noises in the IO inputs, and determines the driver's input request accordingly. The device control subroutine determines the outputs to the LEDs and sound buzzer so as to inform the driver of the system status and to warn the driver when necessary. The device control subroutine determines these outputs based on the state of the HMI state machine, the driver's input request from the driver input subroutine, as well as the fault detected by the fault detection and management subroutine.

The HMI state machine works with the main state machine in the control computers to manage the various functions involved in the VAA system. The HMI state machine changes its state based on the driver's input, the state of the coordination state machine, as well as the fault detection results from the fault detection and management subroutine.

As a top-level fault detection and management for the VAA system, the fault detection and management subroutine not only detects the faults related to the HMI module itself, but also monitors/compares the performance of the two control computers and manages faults reported from the control computers. In addition, the HMI software also includes a second thread for the watchdog for its own operation. The CAN interface subroutine packs the variables into standard CAN format for CAN communications and unpack the received CAN messages into variables to be used by the HMI software. The CAN drivers are the low-level driver that actually handles the sending and receiving of the CAN messages. The low-level drivers include digital IO drivers (to receive inputs from the switches and send outputs to control the LEDs and buzzer).

Components Integration

Following the function blocks in Figure 1-1, the components of the VAA system were integrated into the test buses. The key components include the steering actuator, magnetic sensor modules, DGPS/INS module, control computers, and the HMI. Figure 3-8 shows the VAA components and their installation on the New Flyer Bus for the LTD application. On this New Flyer Bus, the control computers, the steering actuator servo controller, and the HMI controllers, together with relevant power modules and switches, were installed in the refrigerator cabinet. Two magnetometer sensor bars were installed under the bus, one in front of the front wheels and the other about 5 m behind the front door (under the middle door). The LED lights, buzzer, and control switches/buttons were installed close to the dashboard and driver's control panel. The components and installation for the AC Transit application, shown in Figure 3-9, are almost identical with the exception of modifications in the actuator design (more compact) and selections of installation locations.

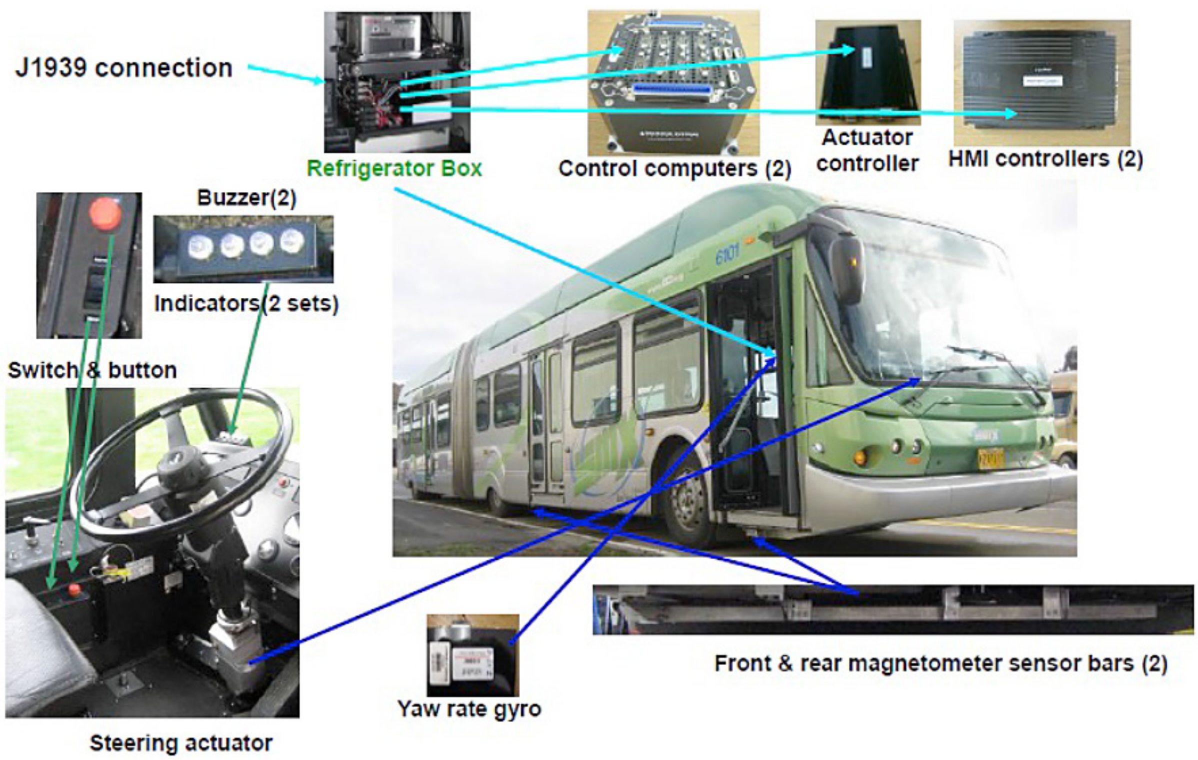


Figure 3-8

VAA system components and installation on LTD 60-ft New Flyer bus

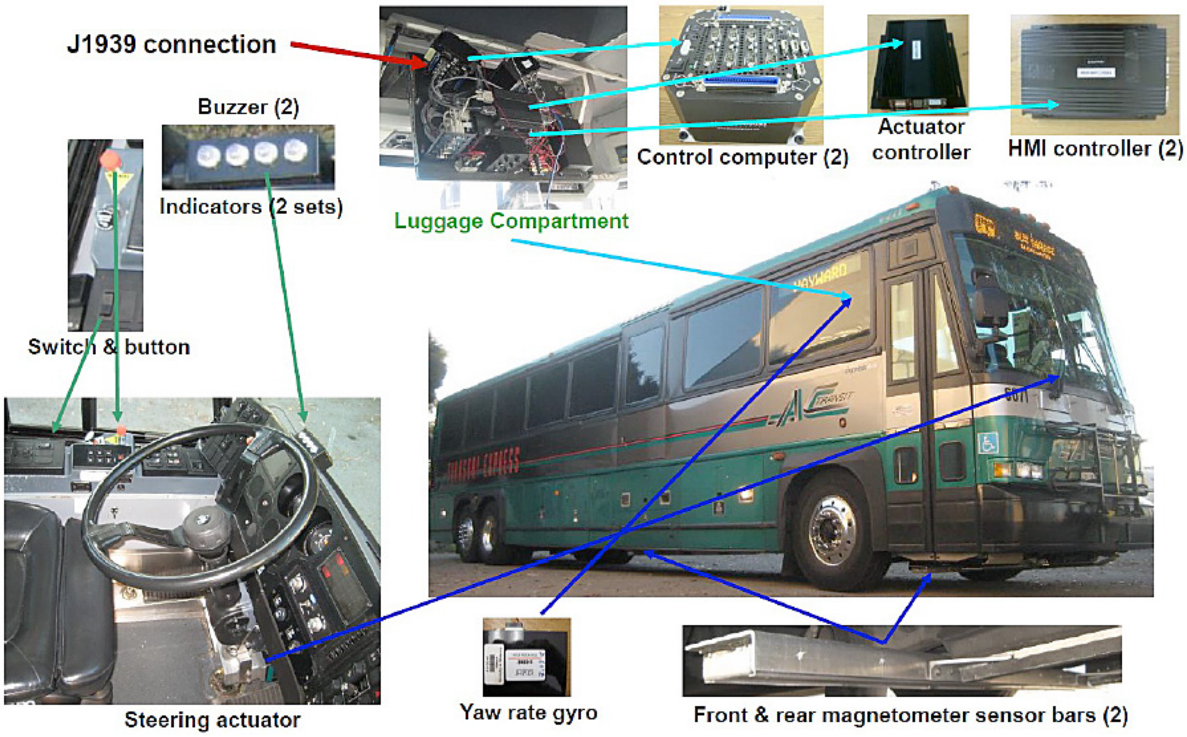


Figure 3-9

VAA system components and installation on AC Transit 50-ft MCI coach bus

SECTION 4

Component and Integration Testing

As discussed in Section 1, VAA system validation included four hierarchical levels of testing: 1) component testing, 2) component integration testing, 3) system testing, and 4) operational testing. This section describes the component and integration tests, including the objectives, scope, resources and responsibility, assumptions for the component and integration testing, and testing methodologies.

Component Testing

As mentioned earlier, the primary objective of the component testing was to ensure that all key components met the respective technical specifications that flow from the VAA system requirements and satisfied the interface requirements and procedures. The second objective of the component testing was to identify and expose any issues with the design, implementation, interface and integration, to assess the associated risks to the project early on, and to communicate all known issues to the project team and ensure that all issues are addressed in an appropriate manner. Achieving this objective requires careful and methodical testing of all key components to ensure that all aspects of the components are tested and all issues are identified and appropriately dealt with.

Test Scope

The component testing included the testing of all key components, including the steering actuator, magnetic sensor modules, DGPS/INS module, control computers, and HMI modules. More specifically, the component tests included testing of the following aspects of each of the above key prototype components:

- Basic component-level performance, such as range, accuracy, consistency, etc.
- Basic interface capability, including sufficient interfaces and data communication capabilities
- Operation of the lower-level software, including operating system, and software drivers
- Basic operational environment capability, including CPU speed and throughput
- Mechanical attributes, including enclosure dimensions, weatherproof or water resistance, as well as ease of installation and replacement
- Electronic attributes, including PCB boards, wiring, connectors, and power regulation

As the component testing was to verify the performance of each individual key component, the following were considered out of scope for the component testing:

- Testing of functional performance above the individual component level, including the application software that is resided in each component
- Testing of interfacing capabilities that are beyond basic driver level data connectivity
- Testing of safety and fault management that is beyond sub-component software driver's error recovery or error reporting capabilities

The above testing was performed at the subsystem level; therefore, tests were conducted during the component integration testing. Upon the completion of the component integration testing, the system testing would then verify the performance and reliability of the VAA system, which would implicitly verify the functional performance, interface capabilities, and safety and fault management of the subsystems as well.

Component Testing Methodology

The general methodology adopted for the VAA component testing included approaches used for the component testing, methods for the anomaly resolution, requirements for test suspension and resumption, and criterion of test completeness.

Basic Test Approach

The basic test approach employed by the component testing was "requirements testing," in which the components were tested and checked against their individual requirements and specifications. Two basic types of testing, component unit testing and component acceptance testing, were included in the component testing. The component unit testing was conducted by the component developers throughout the process of the component development, including prototyping, fabrication, and coding, to ensure that proper functionalities and performance coverage were achieved. The component developers also conducted final component unit testing before delivering the components to PATH. The final component unit testing verifies that the components meet the specifications in the individual developers' SOW as well as other requirements communicated through email and live discussions. The component acceptance testing started after a (prototype) component was delivered to the component test team following a successfully completion of the component unit testing. PATH engineers from the VAA system design and integration team conducted the component acceptance testing with the support of PATH technical staff; the component developers also supported the component acceptance testing by providing hardware and software tools for testing.

Component Testing Process

The component unit testing was conducted in an iterative fashion. Any issues identified in component unit testing were addressed and the corrected components were retested to ensure the issue had been resolved. Due to the time limitations of the project, regression testing[7] was used in the component unit testing to uncover software errors by partially retesting a modified program; however, the final component unit testing was completed to ensure all aspects of the specifications were satisfied.

Any bugs and problems identified in component acceptance testing were communicated to the component developers, who were responsible for correcting the bugs and resolving the problems. After the correction, the component developers conducted component unit testing again before re-delivering the modified components for component acceptance testing.

During each iteration of identifying bugs/problems and taking receipt of the corrected components, several processes were common to different components. These processes included testing of basic functionalities (such as sensing, actuating, communication, mechanical, electrical and environmental factors, etc.), performance (such as processor speed, throughput, sensor accuracy and noise characteristics, actuator response, power consumption and noise rejection, etc.), and reliability. During the testing, the control computer was used as a monitoring device or a data communication tool for testing the other components. The component testing for each component typically had at least 2–3 iterations between the component unit testing and the component acceptance testing.

All bugs that could have an impact on the performance of the VAA functions were resolved before the components exited the component testing phase. The component developers were responsible for communicating to the PATH test team the component unit testing results and the corrections that were made. In each iteration between the two types of testing, the PATH test team held a debriefing meeting with the corresponding component developer to describe the problems and to approve the resolution.

Testing Completeness Criteria

Release of the components for integration into the test bus could occur only after the successful completion of the component acceptance testing. Each component was tested and released to the bus integration phase independently. The milestone target for each component was the start of its integration into the VAA test bus after it had shown to meet or exceed the specifications as defined in the VAA system and interface requirements (Section 2) and the developer SOWs.

[7]The purpose of regression testing was to provide a general assurance that no additional errors were introduced in the process of fixing other problems. Regression testing is commonly used to efficiently test the system by systematically selecting the appropriate minimum suite of tests needed to adequately cover the affected change [8].

Anomaly Resolution

Any problem or bug discovered during the component testing needed to be properly resolved. The method of anomaly resolution included two basic processes: regression testing (bug regression) and problem priority and severity identification (bug triage).

Regression testing, re-test after any changes, was a core method of all testing phases. It attempted to mitigate two risks:

- A change intended to fix a bug/problem fails
- The change has side effects such as unfixing an old bug or introducing a new problem

Any problem or bug that was identified by the component test team was tagged as "problem/bug —needs fixing." All problems or bugs that had been resolved by the component developer were marked as "fixed—needs re-testing." When the corrected component passed through the regression testing, it was considered as "problem closed—bug fixed." Whenever a problem fix failed a regression test, the test team immediately notified the system design team and the component developer.

To optimize the use of the limited resources of any project, continuously determining the priority and severity of the discovered problems or bugs was an important step throughout the testing phase. The priority and severity of a problem referred to how important fixing the problem was to the project and if unfixed how severe the problem would affect the system technically, respectively. To determine the problem priority and severity, project meetings, also called bug triage meetings or bug councils, were held to evaluate the discovered problems and to classify them into categories accordingly. Prior to the determination, the PATH test team gathered enough information about the problem so as to assign the problem into the appropriate category and to communicate effectively to the component developers the problem and its impact.

The VAA project adopted the following scales to describe the severity and priority of a problem or a bug discovered:

- Severity levels:
  - Critical – the problem/bug causes the VAA system fail or crash, or create a safety concern
  - Major – the problem/bug causes the VAA system major functionality or other severe problems
  - Minor – the problem/bug causes the VAA system minor functionality problems

- Priority levels:
  - Top priority (must fix) – Must fix as soon as possible: the problem/bug is blocking further progress of the project
  - High priority (should fix) – Should fix before next testing phase (component integration testing): the problem/bug does not affect the progress of the project but degrades the performance of the corresponding component.
  - Low priority (fix later) – Fix if time permits: the problem does not degrade the technical performance but may affect the system in a minor way such as appearance.

The test lead, project managers, system design and integration teams, and component test team were involved in the decision of the priority and severity. Based on the decision, the team then determined the type of resolution for each problem/bug by classifying it into one of the following three categories: problems/bugs to be fix now, problems/bugs to be fix later, and problems/bugs that will not be fixed. For example, a bug that was determined to be critical and had top priority fell into the category of problems/bugs to be fixed now; a minor and low-priority bug might not be fixed if time did not permit. Accordingly, the team developed a schedule for all "to be fixed problems/bugs." The problems/bugs were then assigned to the appropriate component developer as well as the test team members, who then fixed the problems and reported the resolution back to the component test team. The test lead was responsible for tracking the status of all problems and bugs.

Suspension Criteria and Resumption Requirements

Testing was suspended on the affected component when problems with severity of critical level or major level were discovered during either the component unit testing or the component acceptance testing. In such cases, the testing would not resume until a fix had been found and the affected component had been modified. Testing would be suspended if there was a critical scope or specification changes that would impact the testing plan.

After fixing the bug or the problem, the component developer then informed the test team and provided a detailed report of the fix, as well as additional information to support any additional testing. At that point, the test team regressed the problem and, if the corrected component passed the regression test, continued the remaining component testing.

Test Completeness

The component testing was considered complete for a component when all of the following conditions had been satisfied. First, the PATH test team and the corresponding component developer agreed that 1) all pre-determined test cases had been conducted, 2) the component met all of the functional specifications, and 3) the component software was stable. Second, all problems with top or high priority had been resolved.

Test Results

The key components of the VAA system—steering actuator, magnetic sensor module, DGPS/INS module, control computer, and HMI module—were tested during the component testing. For each key component, features that need to be tested were determined based on the component specifications defined in the system and interface requirements. For each key component, the test results together with the features to be tested, the test procedure, and the acceptance criteria were presented in a table. Problems encountered during the component testing and the corresponding debugging and resolutions were also provided. All VAA components ultimately passed the component testing. Results of the component testing are included in Appendix B.

Component Integration Testing

The primary objective of the component integration testing was to ensure that all key components were properly integrated and met the respective technical specifications that flowed down from the VAA system requirements and satisfied the interface requirements and procedures. Component integration testing ensured that the properly tested components (through component testing) interacted correctly. The second objective of the component integration testing was to identify and expose any issues with the design, implementation, interface, and integration. Therefore, the project team could assess the associated risk to the project early on and ensure that all issues are addressed in an appropriate manner. Careful and methodical testing of all interfaces between key components were conducted so as to ensure all aspects of the components' interfaces and interactions were tested and all issues were identified and appropriately dealt with.

Since the VAA system design adopts a modular system architecture, component integration testing also serves as an important process to reveal faults that signal either inadequate component testing or incomplete interface specifications.

Test Scope

The component integration testing was conducted after the components had successfully passed their respective component testing and had been integrated into larger aggregates. The component integration testing included testing of the following integration aspects of each of the key components in the integrated subsystems:

- Mechanical interface attributes, including locations and methods for components' installation, enclosure dimensions, and connector types
- Electronic interface attributes, including power, connectors and wiring compatibilities, grounding and noise insulation, and impedance matching

- Basic compatibility with the bus operational environment, including bus mechanical and electronic noises induced by vibrations, bus power and other existing bus components
- Operation of the interface software, including operating system capability, processor throughput, and software drivers
- Data interface attributes, including message content and communication rates of the communication between various key components
- Operational performance of the key components in the integrated subsystems

As the component integration testing focused on verifying the performance of the interfaces between the key components, the following were considered out of scope for the component integration plan:

- Testing of basic functional performance within the individual component level, including the full application software that is resided in each component; this testing is within the scope of component testing in the component development phase
- Testing of system performance level that is beyond component integrations; this testing is within the scope of the subsequent system testing that follows the component integration
- Testing of safety and fault management that is beyond component interface software driver's error recovery or error reporting capabilities; this testing is also within the scope of system testing that follows the component integration

Component Integration Testing Methodology

This subsection describes the general methodology adopted for the VAA component integration testing. The detailed methodology includes approaches used for the component integration testing, methods for the anomaly resolution, requirements for test suspension and resumption, and criterion for test completeness. Before the detailed description of the methodology, an overview of all the testing involved in the VAA project is provided to explain how the component integration testing relates to other VAA testing.

Component integration was concerned with the process of combining components into an overall system; therefore, the purpose of the component integration testing was to verify functional, performance, and reliability requirements placed on groups of the key components through physically integrating the components together and testing their interfaces using black box testing.

For the VAA project, the system components were first physically installed into a test bus[8] according to the specifications under the operational environment to test the mechanical and electrical interface performance. Usage of shared data and inter-process communication were simulated by software residing in the control computers and embedded processors to test the data interface between components. Test cases were constructed to verify that all key components of the integrated system interact correctly. In short, the VAA component integration testing ensured that all components functioned appropriately, satisfied the VAA interface requirements and supported the VAA system requirements when they were grouped together. The key VAA components and their corresponding interfaces that were required to go through component integration testing were: the steering actuator, the magnetic sensing module, the DGPS/INS module, the HMI, and the control computer.

Basic Testing Approach

Two integration testing strategies are typically used on a modular system structure such as the VAA system: top-down and bottom-up. The top-down testing is an approach where the top integrated modules are tested and the branch of the module is tested step by step until the end of the related module. In the bottom-up testing approach, the integrated modules at the lowest level are tested first and then used to facilitate the testing of higher level integrated modules. The process is repeated until the integrated module at the top of the hierarchy is tested.

The component integration testing identifies problems that occur when components/subsystems are combined. Since the component testing had been conducted on each key component to ensure its viability before it was combined with other components, the problems or errors discovered in the integration testing were most likely related to the interface between components/subsystems rather than the internal functionality of each component. Thus, the bottom-up approach would help narrow down the possible sources of the problems and simplifies the debugging process. Therefore, the VAA component integration testing adopted the bottom-up testing strategy. On the other hand, the subsequent VAA system testing followed the top-down testing strategy to identify and fix any problems or issues discovered during the system testing.

The basic testing approach employed by the component integration testing was "requirements testing" where each integrated sub-system was tested and checked against its individual interface requirements and specifications. Therefore, for the component integration testing on each sub-system, a set of features to be tested and the acceptance criteria were identified based on the corresponding functional and interface requirements (Chapter 2). Accordingly, the test cases were defined and test procedure was designed.

[8]Before installing the components into the bus, the components are wired together in bench environment at the initial stage of the component integration testing as an initial evaluation of the integration

Component Integration Testing Process

Following the bottom-up approach, the component integration testing was conducted in a hierarchical fashion. In its simplest form, two components that had passed their corresponding component testing were combined into an integrated sub-system and the interface between them was tested. An integrated sub-system, in this sense, referred to an integrated aggregate of more than one component. In the VAA project, the control computers were the core component that communicates with each of the four other key components; therefore, the control computers and each of the four other key components were tested as an integrated sub-system to ensure correct interactions between the control computer and each of the other key components. Subsequently, the integrated subsystems were aggregated into larger subsystems to test the interactions among them. Eventually, all the subsystems making up the VAA system were tested together.

Any issued identified in the lower-level component integration testing was corrected and the corrected interface was retested to ensure the issue had been resolved. Due to the time limitations of the project, regression testing[9] was used in the component integration testing to uncover software errors by partially retesting a modified interface program; however, the final component integration testing was completed on the integrated VAA system to ensure all aspects of the interface and component performance specifications were satisfied.

All bugs that could have an impact on the performance of the VAA functions were resolved before exiting the component integration testing. The component developers were responsible for correcting any component level problem that was discovered during the component integration testing. In such scenarios, PATH test team held a debriefing meeting with the corresponding component developer to describe the problems and to approve the resolution.

Testing Completeness Criteria

The goal of the component integration testing was to establish that the combined VAA components had reached the pre-defined level of interface performance and software stability, and that they were appropriate for the next phase of the VAA project: system and operational testing. Accordingly, the features to be tested and the acceptance criteria were determined based on the VAA system requirements and the interface requirements. The completeness for each key integration and interface was determined after the interface and integration had shown to meet or exceed the respective acceptance criteria. Only after the successful completion of the component integration testing could the VAA system testing, tuning, and operations start.

[9]The purpose of regression testing was to provide a general assurance that no additional errors were introduced in the process of fixing other problems. Regression testing is commonly used to efficiently test the system by systematically selecting the appropriate minimum suite of tests needed to adequately cover the affected change [8].

Anomaly Resolution, Suspension Criteria, and Resumption Requirements

Any problem or bug discovered during the component integration needed to be resolved properly. Similar to the anomaly resolution used in the component testing, the anomaly resolution used in the component integration testing also included regression testing (bug regression) and problem priority and severity identification (bug triage).

Any problem or bug identified by the component integration test team was tagged as "problem/bug – needs fixing." All problems or bugs that have been resolved by the component developer or the PATH engineers were marked as "fixed – needs re-testing." When the corrected components and their interfaces passed through the regression testing, they were considered as "problem closed – bug fixed." If a problem fix failed a regression test, the test team immediately notified the system design team and the component developer, if appropriate.

To optimize the use of the limited resources of the project, the discovered problems or bugs were also analyzed to determine their priority and severity. The same three categories used in the component testing were also used in the component integration testing. The PATH test team assigned each problem to the appropriate category and resolved each problem following the same anomaly resolution process.

Similarly, testing was suspended on the affected components or interfaces when problems with severity of critical level or major level were discovered during the corresponding component integration testing. In such cases, the testing would not resume until a fix had been found and the affected components or interface had been modified. After fixing the bug or the problem, the component integration team or the component developer would inform the test team and provide a detailed report of the fix, as well as additional information to support any additional testing. The test team then performed regression testing on the fix and, if the corrected component passed the regression test, continued the remaining component integration testing.

Test Completeness

The component integration testing was considered complete for an integrated subsystem when all of the following conditions had been satisfied. First, the PATH test team determined that 1) all pre-determined test cases had been conducted, 2) the interface among those components met all of the interface specifications, and 3) the interface and integrated software were stable. Second, all problems with top or high priority had been resolved. No "must fix" problems or bugs remained.

Component Integration Testing Results

The component integration testing was conducted on the 40-ft test bus at RFS. It focused on the interactions and the data communications among the installed components, in addition to verifying that the integrated components still satisfied their respective operational performance requirements. The test environment related to the hardware, software, and the test support tools needed to conduct the component integration testing and includes the environment for setup before the testing, execution during the testing, and post-testing activities. The features to be tested were determined based on the system requirement and interface specifications defined in the system and interface requirements. The major components that were integrated include the steering actuator, magnetic sensor modules, DGPS/INS module, HMI modules, and control computers, as well as the existing mechanical, electrical, and data communication systems of the transit buses that were interfaced with the above VAA components. For each of the key components, three categories of the interface were examined: mechanical installation, electrical power supply, and data communication. The PATH engineers prepared the integration testing software and conducted the component integration testing with the support of the technical staff. The component developers provided specific tools, wiring, connectors, and component level software drivers that were required for the integration testing.

The component integration testing was conducted in an iterative fashion. The PATH test team designed and carried out the test procedures to evaluate the interfaces among key components and the functional performance of the installed individual components. Whenever the test results indicated any failure to meet the interface specifications or any problem/bug, the PATH test team first identified and corrected those errors/bugs if they were created by mistakes or errors during integration or interface. However, when such problems were result of component or firmware problems, the PATH test team then informed the component developers of such issues and returned the component to them for correction. Subsequently, the component developers worked with the PATH test team and developed solutions for the problems. The component developer executed component unit testing before re-submitting the corrected component for component acceptance testing and component integration testing. The PATH test team conducted the integration testing with the corrected component again to ensure the interface specifications and performance specifications were met. Results of the component integration testing are included in Appendix C.

SECTION 5

Field Testing

Upon the completion of component integration tests, system testing and operational testing were conducted in the field. System testing was conducted to ensure that all VAA system functions were carried out according to the system requirements for the VAA applications. Multi-layer functional and multi-period reliability testing was conducted for each component, subsystem, functional algorithm, and operation scenario as well as for each bus and each application. The goals were to establish baseline performance capabilities and verify the system and components' reliability and robustness. Finally, the system testing was conducted to calibrate sensor and control parameters, tune system performance, and verify the performance and operations for the operational tests.

System testing for the LTD New Flyer 60-ft articulated VAA bus was first conducted at the LTD yard track and then on LTD's Franklin EmX BRT route. For AC Transit, system testing of the 50-ft MCI coach was conducted at the PATH RFS test track. The system tests along the SR 92 HOV lane and toll plaza were not conducted due to the timing and resource issues.

Data collection and analysis were conducted to support multiple goals of the VAA project. The specific goals of the data collection and analysis varied depending on the level of the testing. During the system testing, the data collected supported the verification of system performance and reliability. Therefore, the data collection focused on collecting quantitative performance data as well as system fault detection and management data.

To validate system performance and measure operational improvements due to the introduction of VAA, the VAA system incorporated an on-board data acquisition system to record quantitative performance data. To ensure the VAA system's fault detection and management capability (as well as to identify VAA faults encountered in real-world transit operations in the subsequent operational testing), the on-board data acquisition system also recorded faults detected by the VAA system (including both non-critical and critical faults), VAA system fault management activities (including fault tolerant controls, and warning signals provided to the driver), and driver intervention (steering override and/or braking behavior).

The performance measurements and the fault information allowed PATH researchers to monitor system performance and to identify, diagnose, and fix potential problems during the subsystem and system validation tests.

Test Sites

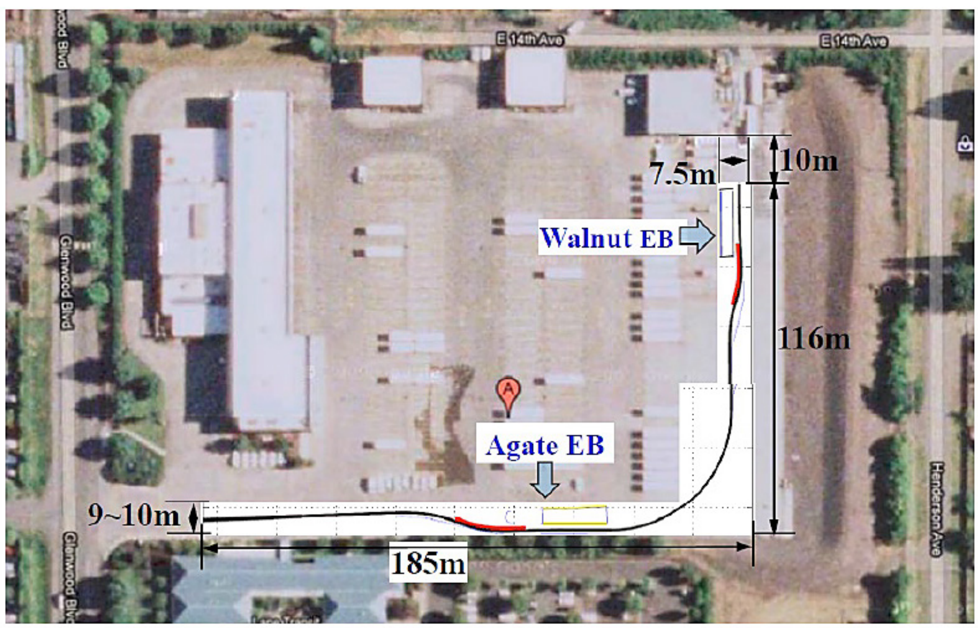
This section describes the locations and features of field testing for LTD and AC Transit VAA-equipped buses.

Test Track at LTD Yard

To facilitate the system testing, a test track was designed and installed at the LTD maintenance yard. The design considerations included the following: 1) the test track should consist of the exact same docking curves at selected stations along the operational EmX BRT route, and 2) the test track should fit within the test facility while leaving adequate space for the bus to turn into and get out of the track. Since docking at the eastbound Walnut Station and the EB Agate Station generally is considered to be the most challenging by operators, the docking curves at those two stations were selected to be duplicated at the test track. To fit into the approximately 745 ft x 413 ft rectangular shape of the maintenance yard, the test track was designed to be an L-shape, with the two docking curves located on the two straight segments; a 90-deg curve with a radius of 40 m connects the two straight segments. Figure 5-1 illustrates the 902-ft test track in the LTD maintenance yard; the black line is the main magnet track, and the red lines are the secondary magnet track along the two docking curves.

Figure 5-1

Test track at LTD maintenance yard (map view)



LTD Franklin EmX BRT Route

After system testing was successfully completed at the test yard, system testing was then conducted on the LTD Franklin EmX BRT route to calibrate sensor and control parameters, tune system performance, and verify the performance and operations for the respective revenue operations. This route connects downtown Eugene and downtown Springfield, the two main hubs for the LTD system. Figures 5-2 and 5-3 show the street view and the map of the Franklin EmX BRT route, respectively.[10] The four-mile Franklin EmX route uses exclusive single and dual bus lanes for about 60% of the route; the remaining 40% operates in mixed traffic. Where a single busway lane is employed, both the eastbound (EB) and westbound (WB) buses travel along the same busway lane by taking turns, and "block signaling" is used to indicate when it is safe for a bus to enter the lane. The bus lanes are 10 ft in width and are separated by an 18-in. curb. Operators can travel up to 45 mph along the corridor. Some portions of the busway employ a grassy median strip.

Figure 5-2

LTD Franklin EmX BRT route (street view)

[10]The EmX is an 11.8-mile BRT system that began service in 2007 as a 4-mile east-west route between downtown Eugene and downtown Springfield (Franklin corridor). In 2011, the 7.8-mile Gateway Extension opened, which runs north–south on Pioneer Parkway from the Springfield Station and provides service to Gateway Mall and Sacred Heart Medical Center.

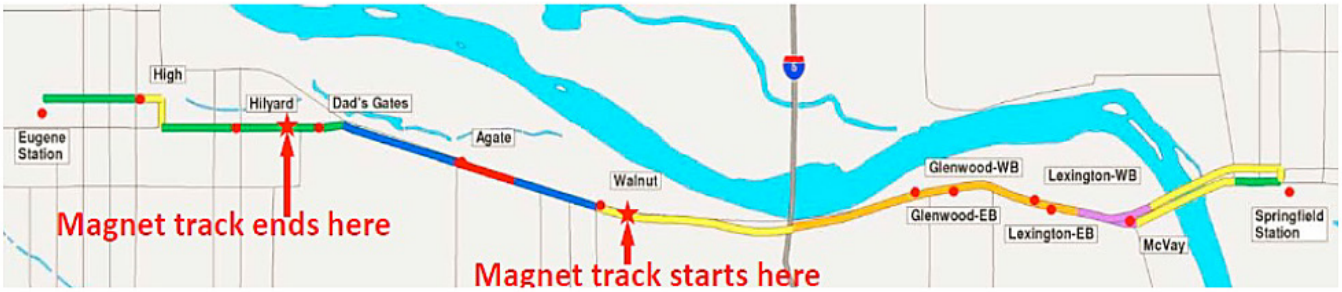
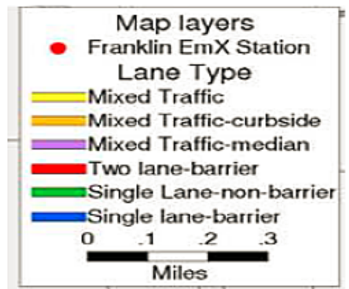


Figure 5-3

Franklin EmX BRT route (map view)

(start and end locations of magnet track marked with red stars)

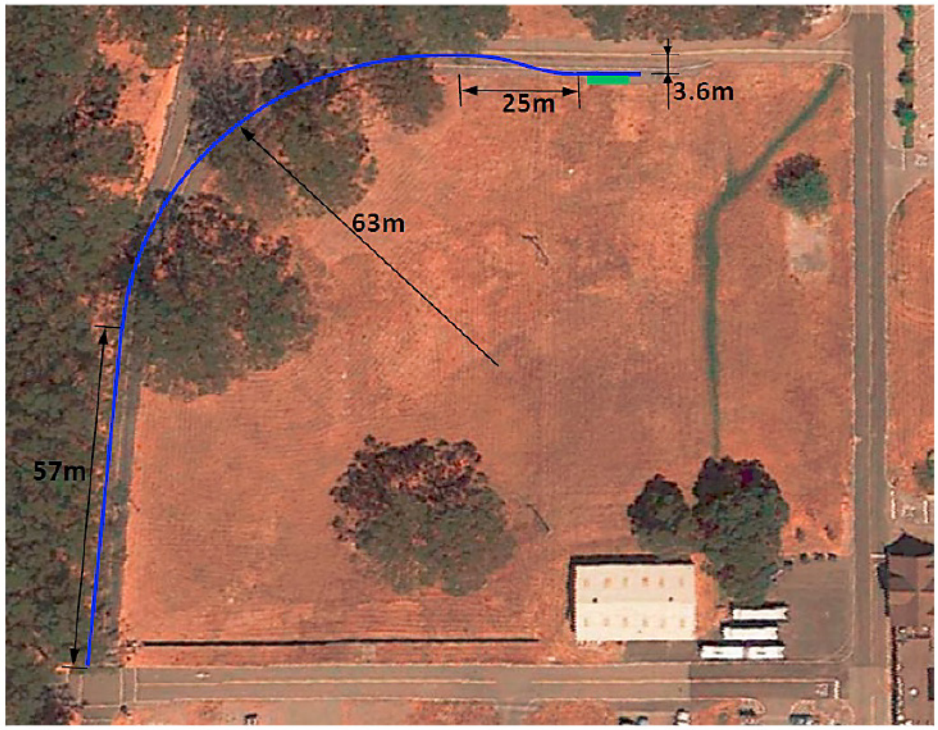


As stated previously, the VAA applications involved precision docking at three stations (Walnut Station, Agate Station, and Dad's Gate Station) in both directions and lane-keeping on the EmX route between these three stations. As shown in Figure 5-2, the EmX route for the VAA application involves dedicated lanes with curb barriers and mixed traffic without barriers as well as a single dual-direction lane and dual single-direction lanes. To install the magnet track along the EmX route, single rare earth magnets were chosen over a stack of four ceramic magnets since a shorter hole-depth was required to avoid re-bars in the concrete busway. Each rare earth magnet was 22 mm (7/8 in.) in height and 25 mm (1 in.) in diameter. The magnets were installed about 1/4 in. below the concrete surface at a spacing of 3–4.25 ft along the designated EmX route, with lead-in magnets for the first station in each direction (i.e., Walnut Station and Dad's Gate Station). The total track length for both directions is about three miles (i.e., 1.5 miles in each direction).

Test Track at Richmond Field Station (RFS)

System testing for AC Transit's VAA applications were conducted at a test track at the RFS. Figure 5-4 shows the map view of this test track (in blue). This test track consisted of a 57-m straight segment, an 86-deg curve with a radius of 63 m, and a 25-m docking curve (a 3-m straight segment between the curve and the docking curve to help smooth the transition). The total length of the test track was approximately 220 m, and the tightest curve, located at the docking curve, had a radius of 32 m.

Figure 5-4
Test track at RFS (map view)



AC Transit M Line

After successful testing at the RFS test track, the system testing was planned to be conducted on the segment of the AC Transit M Line described earlier to calibrate sensor and control parameters, tune system performance, and verify

the performance and operations for the respective revenue service operations. Figure 5-5 shows the map of the AC Transit M Line route, and Figure 5-6 shows the MCI coach passing through the narrow toll booth preceding the San Mateo Bridge. The 10-ft-wide toll gate is a challenge for bus drivers to maneuver the 9.5-ft (8.7-ft wide + 0.8-ft mirror) MCI coach safely through the gate. Despite the fact that bus drivers typically need to reduce speeds to below 5 mph, the mirrors of the bus sustain damaged from time to time. The VAA lateral control/lane-keeping application was expected to guide the bus through the booth with increased speeds and improved safety.

Figure 5-5

AC Transit M Line route

Figure 5-6

AC Transit's M Line and toll booth

An approximately 2.8-mile section of HOV lane was also chosen for the VAA lateral control/lane-keeping application. The magnet track was installed along the centerline of the HOV lane, starting at about 655 ft before the overpass of Industrial Boulevard and ending at about 328 ft after the San Mateo Bridge toll plaza. Figure 5-7 shows the map view of the magnet track, and Figure 5-8 shows the magnet track through the toll plaza.

Figure 5-7

Magnet track along AC Transit M line (WB HOV lane on SR 92)

Figure 5-8

Magnet track at San Mateo Toll Plaza

Driver Operation and Training

The PATH team developed and executed VAA system driver training with the assistance of the transit agencies. The following sections highlight the driver training conducted as a part of the project. Since the VAA project included revenue service operations at Eugene, one of the first deployments of automatic steering in the US, the development and delivery of driver training under this project should provide valuable lessons for future deployment of transit automation.

VAA System Operations and Driver Interactions

This section describes basic VAA system operations; knowledge of system operation also forms the background materials needed for development of the driver training procedure. The section is organized into three subsections: basic understanding of VAA operations, normal operational procedure, and basic understanding of VAA warnings.

Basic Understanding of VAA Operations

Three basic elements are involved in operating a VAA system in a bus: turning on and off the VAA system, activating the VAA steering control function, and deactivating the VAA steering control function. They are described as follows.

- Turning the VAA system on and off:
  - The VAA system is automatically turned on whenever the bus "ignition" dial is in the ON position at Day-Run, Night-Run, or Night-Park position.
  - The SYSTEM READY (amber LED) indicator flashes during the booting –up process of the control computers. Once the amber LED is steadily lit, the VAA system is on and the boot-up is completed.
  - The VAA system is automatically turned off whenever the bus "ignition" dial is in the OFF position.
- Activating (engaging) the VAA automatic steering control function:
  - The VAA steering control function activation is basically a two-step process: 1) the VAA system is in the AUTO READY state (green LED on) and 2) the driver pushes the AUTO switch.
    - > Once the VAA system is successfully booted up (amber LED on), the AUTO READY (green LED) indicator will be on after the VAA system has detected the magnetic track.
    - > The driver can then push the AUTO switch whenever the green LED is on; the automatic steering function will then be activated, and the AUTO (blue LED) indicator will be lit when the bus steering is under automatic control.

- Deactivating (disengaging) the VAA automatic steering control function (three ways):
  - Driver can override the VAA automatic control by actively steering the steering wheel. The AUTO indicator (blue LED) will be off, and the MANUAL indicator (green/amber LED) will be on.
  - The driver can turn off the VAA automatic control by pushing on the MANUAL switch. The AUTO indicator (blue LED) will be off and the MANUAL indicator (green/amber LED) will be on.
  - The driver can turn off the VAA automatic control by pushing down the EMERGENCY button. The AUTO indicator (blue LED) will be off and the FAULT indicator (red LED) will be on, signaling no power to the actuator.

Normal Operation Procedure

Before the VAA bus can be used in automatic control mode, the responsible maintenance or operations supervisors need to make sure that 1) the actuator power safety switch (in an outside panel of the bus) is on, and 2) all of the VAA system circuit breakers (inside the instrument cabinet) are on. These switches should be accessible to and turned off only by a maintenance or operation supervisor, either for maintenance or to shut down the VAA automatic control operations. These switches should remain on for VAA operations, and they should not be accessible by bus drivers. If any switches are off, the red LED will be on and the VAA system cannot be activated.

Bus operators should operate the VAA system according to the safety rules set up by the transit agency. The following procedure describes the normal VAA operations along the LTD EmX magnetic track at Eugene:

- Turn on the bus and drive the bus normally before reaching the magnetic track (WB from before Walnut Station and EB from before Dad's Gate Station)
- Once the bus has detected the magnetic track, the green LED will be on and a short beep will sound.
- The operator can push the AUTO switch any time after the green LED is on.
- VAA automation starts when the blue LED is on.
- The operator should maintain proper speeds for the curves on the track. The amber LED will start flashing when the speed is too high for the curve; a buzzer will sound when the speed exceeds 15% of the threshold speeds.
- The amber LED will also flash when the bus is within 5 ft of the designated stop location for each of the stations. This is just a convenient function for the operator to support his/her operation.
- The operator can turn off the VAA automation by overriding through the steering wheel or pushing the MANUAL switch at any time, or at the end of the magnetic track (after the station docking).

- The red LED will flash and buzzers will sound before the bus reaches the last magnets if the driver forgets to deactivate the automatic control.

Basic Understanding of VAA Warning

A warning (sound and/or fault LED) to the driver is initiated when a functional fault or failure of the VAA system is detected by the VAA fault detection and management functions. The two most common warning and response scenarios are described below based on whether the bus is under automatic steering control or not:

- If the fault is detected during automatic control:
  - Warning sequence will be initiated: red LED flashing, buzzers beep continuously.
  - Frequency of beeps indicates urgency of required driver response.
  - Driver should slow down and take over control as quickly as possible.
- If the fault is detected during manual driving:
  - Fault indicator will be on: red LED on and one short beep from buzzer at time fault is first detected.
  - No immediate driver response needed; automatic control of VAA system cannot be initiated (no green LED).

As described above, no driver action is required when a fault is detected when the bus is under manual control; the VAA system will simply light up the red LED and prevent the driver from engaging the VAA control function. No specific training is necessary for such fault scenarios. However, when the bus is under automatic control, knowledge of the consequences of system failure and an appropriate corresponding response are critical to the safety of the VAA system operation.

Three basic fault types (when such a fault occurs under VAA automatic control) are described below in more detail with their specific warning patterns and proper driver responses:

- Minor fault:
  - Fault type – any operational or system fault that the VAA system can handle without noticeable degradation in performance and safety.
  - Warning pattern – red LED on, with only one short beep when first detected.
  - Driver response – no specific or immediate driver response required.
- Major fault:
  - Fault type – any component or system failures that are protected by the hardware and/or software redundancies of the VAA system; degraded controllers are activated to sustain VAA operations for at least a few seconds under such failures.

  - Warning pattern – red LED flashing with loud, continuous beeping at lower frequencies; based on suggestions from instructors during EmX fault testing, beeping gets faster and faster even when degraded controller can sustain system operation. VAA control will also be automatically terminated when beeping becomes high frequency.
  - Driver response – driver needs to put his/her hands on steering wheel upon warning and prepare for overriding with steering wheel; can override through steering wheel at any time. Once VAA automatic control function terminated, warning sound will stop, and red LED will remain lit.
- Critical fault:
  - Fault type – multiple component or system failures that results in VAA system incapable of sustaining safe operation; VAA actuator control is terminated.
  - Warning pattern – red LED flashing with loud, continuous beeping at high frequency.
  - Driver response – driver should put his/her hands on steering wheel immediately and take over steering function. Once VAA automatic control function terminated, warning sound will stop, and red LED will remain on.

VAA Driver Training

This section provides an overview of the driver training procedure and details the various elements used in driver training, including background information for instructors/trainers and drivers, suggested training procedure for normal and emergency operations, driver training schedule and timeline, and issues involved in human subject studies.

Development of Driver Training Procedure

This section relates to the development and implementation of the VAA driver training procedure in the deployment phase of the VAA project. Since deploying an automated steering function on a transit bus is still a relatively novel concept for US transit agencies and operators, very limited experience with such deployment exists in the industry. Therefore, the driver training process was also a design consideration during the development of the VAA system functions and operational concepts and the interfaces between the driver and the automated bus. The development of driver training in this project was a combined effort among VAA system developers and the transit agencies as well as the drivers who participated in the testing and training processes.

The VAA system was designed to automatically follow the magnetic track and perform accurate steering control functions with high robustness. In addition to controlling bus speed and activating and de-activating VAA functions, drivers were responsible for monitoring the operational environment and taking over the steering control functions whenever he/she deemed it necessary or when the VAA system prompted him/her to do so. In that aspect, the design and development of the VAA system needed to consider the driver as part of the overall system. Thus, the VAA functions were designed with the driver either as a part of the overall system functions or as a variable in the operational scenarios.

PATH developed baseline training materials and generated driver training guidelines and trained instructors/trainers for the transit agencies. The transit agencies recruited the bus operators, supported the overall training logistics, and integrated the VAA driver training into their driver training procedures. Feedback from the transit agencies and instructors during testing and tuning of the VAA system not only contributed greatly to the design of the driver training procedure, but also helped the development team adjust the VAA system design and calibrate the parameters in the HMI design to better fit the transit operations.

The major milestones of the driver training included completion of instructor/trainer training for LTD in April 2013 and completion of the first sessions of driver training by LTD instructors/trainers in June 2013. At the end of the project, more than 28 LTD operators were trained and used the VAA system during revenue service.

Driver Training Procedure Overview

The driver training process consisted of the following two stages:

- Stage I – The PATH VAA developers conducted detailed training sessions with a few instructors selected by the transit agencies and continuously updated the training procedure and background information based on feedback from the instructors and improvements resulting from VAA system calibrations.
- Stage II – The instructors further modified the training procedure based on the information provided by the PATH developers in accordance with the existing transit agency training procedures. The general group of the drivers who used the VAA system during revenue service were then trained by those instructors using the modified training process.

Instructors and Participating Drivers

Instructors were selected from the existing instructors from the transit agencies. For this project, they often performed the functions of the "test drivers" for tuning and calibrating the VAA system during the development and deployment phase of the project.

The recruitment of participating drivers was conducted by each transit agency. Each bus driver's job is a unique combination of the characteristics of routes, times of day, and days of the week. In a process known as "bidding," drivers select their runs by reporting to a central location, usually in seniority order, to select their runs. During the driver-route bidding process prior to the start of VAA revenue service, the transit agencies informed drivers of the routes on which there would be VAA system testing and attempted to assign only drivers interested in participating in the VAA operations. If assigned to a VAA-equipped route, drivers could elect to sign a consent form, be part of the evaluation, and drive the VAA-equipped bus. In the case of the LTD EmX route, all drivers of a VAA-equipped bus signed a consent form and agreed to use the VAA system. The driver training for the revenue service was repeated for new drivers after a new bid process.

Stage I of Driver Training Process

For the component testing and initial system testing, LTD built a VAA test track in its bus yard, and AC Transit used the track at RFS. These two test tracks contributed greatly in the development of the driver training procedure.

It is worthwhile to note that the EmX magnetic corridor includes both exclusive (single and dual) bus lanes with a curb barrier and mixed traffic lanes without a barrier and crosses 15 intersections. All curbed sections are narrow (typically 10 ft), and the corridor is very curvy, with a total of 36 curves (excluding seven sharp docking entry and exit S-curves), eight of which have a radius less than 100 m (smallest radius 46.6 m). A bus can reach 40 mph in this corridor. Precision docking is required at six locations (three stations in each direction), and the VAA system needs to align both sections of the articulated bus to the platform within 6 cm without touching the platform or curb, despite variations in driver speed profiles. Such a challenging BRT route highlights the important role the yard track played in the introduction of VAA automated control to bus drivers during the initial training phase.

The instructors assigned by the transit agencies became the first drivers to assist in the performance testing of the system. Prior to each instructor's first use of the VAA system, a PATH engineer conducted an informal driver training procedure. The procedure was then updated each time for a new instructor. During this phase, the instructors worked closely with the system engineers from PATH. For LTD, after the system was fine-tuned on the test track, the instructors who assisted in fine tuning the system then helped test the system on the EmX route (without passengers on the bus). This phase continued until the LTD instructors felt comfortable with the system performance to start the field operational testing. Thus, instructors were effectively a part of the VAA development team and provided the project engineers with valuable feedback about the system during the entire system testing period.

Stage II of Driver Training Process

Stage II driver training consisted of two parts: training on the test track at the LTD bus yard and training on LTD non-revenue runs (i.e., without passengers). Because the project ended before field operational testing could commence for AC Transit, Stage II training did not take place for AC Transit.

Drivers assigned to the VAA bus route were asked to sign a consent form for participation. All consenting drivers were required to complete VAA driver training to become familiar with the VAA system and learn how to use it. The training was part of the driver's normal work day and was conducted by an instructor who was either trained by PATH engineers or by an instructor trained in Stage I. Stage II training included the following:

- A brief explanation of how the system works.
- An inspection of the bus showing where the key VAA equipment is installed.
- An explanation of the driver interface (i.e., displays and controls), possible failures that could be encountered, and how to respond to them.
- Demonstration drives by the instructor.
- Practice driving with an instructor present; the participating drivers first practiced on the test track and then on the bus route, with as many runs as necessary until they felt comfortable with the system.
- Several fault testing runs in which the instructor turned off the power of various system components so the driver could experience the failure and practice the response.

The explanation session and training on the test track typically took less than one working day. LTD designed the format for the non-revenue training runs and determined the completion criteria. After the driver training, the participating drivers were certified to use the VAA system.

Driver Training Background Materials

Because the VAA system is a new technology in the transit industry, a critical element of the deployment process was to answer questions from drivers so they would feel comfortable with the VAA system and its use. Therefore, it was important to provide sufficient background information to the instructors so they could answer questions raised by the drivers in training. To facilitate the VAA driver training conducted by LTD instructors, PATH engineers provided the following to the instructors:

- VAA project background – project objectives, participants, technologies used, test sites, and key tasks and responsibilities

- VAA system descriptions – VAA system functional blocks, components installed in the bus, VAA functions, corresponding performance, and possible limitations of the VAA system

Suggested Driver Training Procedure

This section describes the suggested driver training procedure based on the accumulated experiences of VAA system developers and instructors during VAA testing and deployment at LTD. The training procedure was designed specifically for LTD EmX driver training; for other transit operators, it may serve as a starting point for training procedure design, with adjustments considered according to their specific transit VAA operations. The training methodology adopted should be tailored to fit into the training already used by each transit operator.

- Prior to first run using VAA control:
  - Instructor helps new driver acquire basic understanding of VAA system, meanings and use of driver interfaces, override procedure, normal and emergency operations, and safe operation procedure, either in a classroom with presentations or in a bus with handouts and discussions.
  - New driver rides along with instructor on test track to become familiar with operations, track layout, and simulated stations.
  - New driver practices pushing MANUAL/AUTO switches and pushing/releasing emergency button.
  - New driver operates VAA bus manually without engaging VAA control on test track a few times to become familiar with docking curves and appropriate speeds for each section of track, during which he/she observes LED indicators and learns indicator meanings and appropriate responses.
- First few runs using VAA control on test track:
  - New driver drives slowly, identifies AUTO READY indicator (green LED), pushes AUTO switch after green LED is lit, and maintains control of bus speed after blue LED is lit (i.e., bus is under automation).
  - New driver stops at each station's designated stop.
  - New driver practices "override" after last station.
- Runs with VAA control on test track:
  - New driver practices driving at different speeds under VAA control, including stop and go, and at speeds exceeding suggested operational speeds.
  - New driver practices override and other means of engaging and disengaging VAA control under various speeds and operational scenarios.
  - New driver creates and experiences various operational faults under guidance of and explanation from instructor.

- Fault testing after getting comfortable with normal operations:
  - Instructor helps new driver conduct various fault testing by cutting power off to any one or combination of following components:
    > Front magnetic sensor
    > Rear magnetic sensor
    > Any HMI processor
    > Actuator processor
    > Any control computer
  - New driver experiences waning generated by VAA fault detection and management and practices corresponding response based on warning from VAA system. Instructor may start fault testing by letting driver know before he/she cuts off power to specific components or may cut off power to components without any hint to driver once new driver becomes comfortable with fault responses.
- EmX training without passengers:
  - Instructor determines when new driver is ready to be trained on EmX corridor.
  - New driver rides with instructor on EmX track to get familiar with VAA operations.
  - Instructor reminds new driver of safe operations procedure.
  - New driver drives slowly along EmX corridor, engages VAA control according to VAA indicators, follows magnetic track with conservative speeds, and stops at each station's designated stop.
  - New driver practices driving at different speeds under VAA control, including stop and go, and at speeds slightly exceeding suggested operational speeds.
  - New driver practices override and other means of engaging and disengaging VAA control under various speed or operational scenarios.
  - New driver creates and experiences various operational faults under guidance of instructor.
  - Based on discretion of instructor, and if safe environment allows, new driver may practice fault testing.
  - New driver practices VAA control as if bus is carrying passengers under regular revenue service operations until both driver and instructor feel comfortable operations.
- EmX revenue service with instructor:
  - In accordance with existing LTD training procedure, once instructor is satisfied with new driver training performance, new driver can start revenue service using VAA control with instructor on-board for several runs.

– Instructor determines when new driver can drive VAA bus for regular revenue service without instructor on board according to criteria set by LTD operation.

Driver Training Schedule and Timeline

The LTD VAA-equipped bus started revenue service on June 10, 2013, and official LTD VAA driver/operator training started on April 25, 2013. Prior to training, two LTD instructors were trained by VAA developers who supported testing and performance calibration of the VAA system; their feedback and suggestions provided valuable information for driver training and VAA operations. Between May and October 2013, 23 drivers from 3 bids were trained by the instructors, and all trained drivers used the VAA system in revenue service. The VAA bus was assigned to revenue service operations from 6:00 AM to 10:00 PM all days of the week, and all drivers assigned to the VAA bus consented to using the VAA system. In September and October 2014, 6 new bus operators were trained, bringing the total number of operators trained to 28.

After every new bid process, some drivers who had not been trained for the VAA-equipped bus were assigned to the VAA bus operational slot, so VAA driver training had to be repeated for these new drivers. During this period, the new drivers drove the VAA bus under the manual mode during his/her designated time slots before being certified to engage the VAA control.

VAA revenue service at LTD was suspended in October 15, 2013, due to contractual issues between the University of California and Caltrans; revenue service resumed in October 11, 2014. A new driver training session was conducted for new drivers from the new bid process prior to that day.

As noted, official driver training was not completed for AC Transit applications. One instructor was assigned to support the tuning and calibration of the VAA system along the HOV lane and toll plaza on SR-9; had driver training continued for AC Transit, training on SR 92 would have been a part of the testing procedure for the VAA-equipped MCI coach on the highway. Lane closure with shadow vehicle protection would have been used during the first few nights of training and automated vehicle control testing sessions on SR 92. The tests and training would have started at low speeds and gradually increased in speed as system performance was confirmed. Then, additional drivers from AC Transit would have been trained by the AC Transit instructor.

Human Subject Study Issues

The Committee for Protection of Human Subjects (CPHS) serves as the Institutional Review Board (IRB) for the University of California, Berkeley. All institutions engaged in human subjects research supported by federal funds must have in place a written assurance to the US Department of Health and Human Services (DHHS) Office for Human Research Protections that the institution complies with federal regulations and policies for the protection of human subjects. The primary objective is to ensure the protection of the rights and welfare of all human participants in research conducted by university faculty, staff, and students.

Accordingly, appropriate protocols and a consent form for participating in the VAA project were submitted to and approved by the CPHS. The submitted protocols answered questions about the VAA project and the research and organization background. Also addressed were issues relating to human subject studies including recruitment, screening, compensation, risks, and confidentiality. Some major topics related to the use of human subjects in the VAA project are explained below.

Recruitment

The recruitment of bus drivers was conducted by the transit agency. Typically, drivers are required to rotate through shifts and routes that must be filled. Although the bidding process varies by agency, it generally involves drivers placing requests and management filling those requests based on a system defined by the transit workers' union (e.g., priority by driver seniority). Before the driver-route bidding process, the transit agency informed drivers of the route for the VAA system testing. During the bidding process, the transit agency then tried to assign to the route only drivers interested in participating in the study; if assigned to a VAA route, a driver could decide to sign a consent form, be part of the study, and drive the VAA-equipped bus.

Screening

Participants were required to be bus drivers employed by the transit agency and who volunteered to be assigned to drive a VAA-equipped vehicle. No pre-screening of the potential participants was conducted in this project.

Compensation

No compensation was provided to participants, either monetary or non-monetary, by the project. However, study participants were drivers employed by the transit agency and were entitled to regular and overtime pay as prescribed in their union contract.

Risks

Two general risks for participants were associated with this study: being involved in a crash and breach of confidentiality. The risk of being involved in a crash during the study could be related or unrelated to the VAA system being tested. However, the system was not intended to take the place of the driver, and the driver was in control of the vehicle at all times. Related to the risk of a breach of confidentiality, although the data collected did not include any driver information, it contained time stamps that could be used in conjunction with the transit agency schedule to identify who was scheduled to drive the bus.

To minimize the risk of crashes related to the VAA system, the system was designed with fault detection capabilities and redundancy of all major components. Drivers underwent a training process designed by both the system developer and the transit agency that included practices of responding to system failures and taking over control of the bus. In addition, the driver was always in control of the vehicle speed since the VAA system did not impact the longitudinal control of the bus. As testing was conducted while drivers were employed by the transit agency, any study-related injuries would be on-the-job and covered under the agency's worker's compensation insurance program.

Confidentiality

Driving and VAA system data collected was shared with an independent evaluator, the National Bus Rapid Transit Institute (NBRTI), which was selected by FTA. All data provided to NBRTI were anonymous, without any personally-identifiable information of drivers.

Informed Consent

Informed consent was obtained by the instructors at the time of or before the bus driver was trained on the VAA system. The "Consent to Participate in the Vehicle Assist and Automation Pilot Program" form is included in Appendix D for reference.

System Testing

System validation testing was necessary to ensure that the VAA system worked correctly and consistently before introducing it on public roadways. Therefore, system testing was conducted for each of the test vehicles prior to their deployment for field operational testing. The goals of the system testing were to establish baseline performance capabilities and verify system and component reliability and robustness on the test tracks and then move to the VAA operational routes to calibrate the systems and verify the performance for operations on the selected LTD and AC Transit routes.

Extensive subsystem and system level testing were carried out on the test track at RFS or at the LTD maintenance yard. Multi-layer functional evaluations were conducted for each subsystem, including the lateral sensing system, steering actuator, and control algorithms and for each operating scenario. One critical element of the system testing was fault testing, which included detecting and managing the faults of components, subsystems, and the system. The purpose of the fault testing was to ensure that the system could detect faults and safely handle failures, as functional safety is the key prerequisite for public road testing.

System Validation Testing for LTD Applications

Scope of LTD System Tests

The VAA system for LTD provided lane-keeping and precision docking on the Franklin EmX BRT route. One articulated New Flyer bus was equipped with VAA technology for testing on a selected section of the route.

The VAA system employed magnetic marker sensing for steering control and used a mid-range DGPS/INS integrated system (with differential signals from a satellite-based Wide Area Augmentation System [WAAS]) for data analysis and comparison. Accordingly, the system validation tests for the LTD application focus on tests of magnetic marker sensing. The system validation tests were conducted on the test track at the LTD maintenance yard and then on a selected section of LTD's Franklin EmX BRT route. In this process, any modification to the software was verified on the test track before it could be tested on the public roadway. Appropriate safety measures were in place before the LTD test driver could take it on the EmX route.

VAA Performance Characterization on LTD Test Bus

The goal of the VAA performance characterization was to establish a baseline system performance by calibrating sensor and control system parameters and tuning system performance. Before the system validation tests on the LTD test bus were conducted, the PATH test bus was used to verify the VAA system design and establish baseline performance. VAA components were integrated on the PATH test bus, and subsystem level tests were conducted to ensure the components were working correctly. Low-speed tests were conducted by PATH researchers on the test track at RFS for sensor calibration and control system tuning. The test track included a docking station for testing the precision docking function so the control system could be tuned for basic vehicle guidance and precision docking functions. After initial verification of the VAA system on the PATH test bus, the VAA components were integrated on the LTD test bus and the bus was moved to Eugene.

The VAA performance characterization of the VAA system on the LTD test bus included two stages. First, low-speed tests were conducted by PATH researchers at the LTD maintenance yard test track to tune and establish system performance. The yard track contained replicas of the two most difficult stations for docking along the EmX route. Sensors were calibrated, and the control system was tuned to achieve the preferred mixture of lane-tracking accuracy and ride quality. Relevant performance data, including lane-tracking accuracy (lateral offsets), lateral accelerations, and docking accuracy, were recorded to facilitate performance evaluation and system tuning. The experience gained from testing the PATH test bus benefited the tuning process. As explained earlier, appropriate levels of safety functions, such as fault detections and degraded controls, were implemented and tested on the LTD yard track before any testing was conducted on the EmX route. Test drivers were selected from LTD trainers who were introduced to the VAA system. These trainers became part of the development team as research drivers for system testing along the EmX route.

Second, after the initial tuning was complete and the test drivers were trained, testing on the Franklin EmX BRT route commenced. The daily scheduling of this testing was determined by LTD to minimize interference with normal BRT operations. Performance data were recorded and evaluated, and PATH researchers adjusted the control system parameters to achieve a range of performance characteristics so the trade-off between tracking accuracy and ride quality (partly according to test driver input) were quantified on the LTD BRT route. Since LTD drivers were required to drive the VAA-equipped bus along the public roadway, the two PATH researchers were always on board the bus when it was tested during this phase of testing.

VAA Robustness Validation on LTD Test Bus

After the control parameters were selected, the LTD test bus was driven along the Franklin EmX BRT route repeatedly to measure the consistency of the steering performance and identify any conditions in which the VAA system and its components experienced failures or the VAA performance exceeded acceptable bounds in tracking accuracy or ride quality. These tests were conducted in off-peak periods to minimize potential interference with normal transit operations.

The LTD test bus was driven along the BRT route at speeds up to the normal speed limit for a predetermined number of times and performed precision docking at each station where precision docking was planned for a predetermined number of times. The number of times for these tests was typically determined based on the available schedule of the transit agency and the operators, the time required for each test, and prior test results. During each test run, the on-board data acquisition system recorded all performance measurements, which were analyzed to evaluate the consistency and robustness of the VAA system.

System Validation Testing for AC Transit Applications

Scope of AC Transit System Tests

The planned AC Transit applications included lane-keeping on an HOV lane and through the San Mateo Bridge toll plaza on AC Transit's M Line. A three-mile section of HOV lane on SR 92, from Hesperian Boulevard to the San Mateo Bridge toll plaza, was equipped for vehicle lateral control, and one 50-ft MCI coach was equipped.

According to plan, the MCI coach test bus was to use two VAA sensing technologies, individually and in combination: 1) magnetic marker sensing and 2) DGPS/INS. Although magnetic marker sensing is highly reliable and accurate, GPS reception quality is affected by many factors, typically a combination of the surrounding environment (aggregated factors from blockages and reflections of nearby buildings, signs, trees, and stations), the GPS solution conditions, and the noise and operational characteristics of the supporting sensor units (e.g., noise in the INS or other motion sensors). Therefore, active vehicle guidance (automatic steering) based on DGPS alone was to be tested only during specific controlled tests for comparative performance evaluation; it was not to be tested in revenue service.

VAA Performance Characterization on AC Transit Test Buses

To establish baseline system performance, the VAA performance characterization for the AC Transit application followed the same procedure as that for the LTD application. Prior to the system validation tests on AC Transit test buses, a PATH test bus was used to verify the VAA system design and establish baseline performance. VAA components were integrated onto the PATH test bus, and subsystem level tests were conducted to ensure those components were working correctly. Low-speed tests at RFS were conducted by PATH researchers for sensor calibration and control system tuning. After initial verification of the VAA system on the PATH test bus, the VAA components were integrated into the AC Transit test bus and verified for VAA performance characterization.

The AC Transit performance characterization of the VAA system included two stages. First, low-speed tests were conducted by PATH researchers at the RFS test track to tune and establish system performance. Sensors were calibrated, and the control system was tuned to achieve the preferred mixt of lane-tracking accuracy and ride quality. Relevant performance data, including lane-tracking accuracy (lateral offsets) and lateral accelerations, were recorded to facilitate performance evaluation and system tuning. The experiences gained from the testing with the PATH test bus and the LTD bus benefited the process. Appropriate levels of safety functions, such as fault detections and degraded controls, were implemented and tested on the RFS track before any testing was to be conducted on the track along the HOV lane. Prior experience gained from fault testing on the LTD bus made this process easier for the AC Transit bus.

Second, after tuning was complete and baseline system performance was established, the bus was to be tested at highway speeds on the SR 92 HOV lane and at lower speeds passing through the San Mateo Bridge toll booth. Performance data were to be recorded and evaluated, and, if necessary PATH researchers would adjust the control system parameters to achieve a range of performance characteristics so the trade-off between lane-tracking accuracy and ride quality could be quantified. In both stages, the two VAA sensing technologies—magnetic marker sensing and DGPS/INS technologies—were to be tested both individually and in combination to show the performance trade-offs for each sensor technology. Since an AC Transit driver was required to drive the VAA-equipped bus during this testing phase, similar to the LTD applications, he/she needed to be trained by PATH researchers beforehand. Due to the resource constraints created by the delay from the contractual issues, the VAA project completed only the first stage of system testing described above.

VAA Robustness Validation on AC Transit Test Buses

As indicated, the robustness validation on AC Transit did not occur. According to the original system testing plan, after control parameters had been selected and performance of the VAA system on the AC Transit test bus had been established, robustness validation of the VAA system on the AC Transit test bus was to be conducted. The test bus was to be driven through the test section on SR 92 repeatedly to measure the consistency of the steering performance and to identify any conditions in which the VAA system or components experienced failures or the performance exceeded acceptable bounds in tracking accuracy or ride quality. These robustness validation tests were to be conducted in off-peak traffic periods to minimize potential interference with other road users.

The bus was to be driven in the HOV lane at speeds up to the normal speed limit for a predetermined number of times. The bus also was to be driven through the bridge toll booth for a predetermined number of times. The number of the times for these robustness validation tests was to be determined based on available schedule of the transit agency and operators, time required for each test, and prior test results before the validation tests.

During each test run, the on-board data acquisition system would record all the performance measurements, which would be analyzed to evaluate the consistency and robustness of the VAA system.

System Validation Test Results: VAA Application at LTD

The automated VAA steering control system provided lane-keeping and precision docking (with speed controlled by the driver) at LTD's Franklin EmX BRT route. The 3-mile (1.5 miles in each direction) VAA segment included both exclusive single and dual bus lanes with a curb barrier as well as a mixed traffic lane without barrier. The 3-mile segment crosses 15 intersections, and the curbed section is narrow (typically 10-ft). The segment is also very curvy, with 36 curves (not including 7 sharp docking entry and exit S-curves), 8 of which have a radius less than 100 m (smallest is 46.6 m). The bus can be operated at speeds above 40 mph.

Before the VAA bus was tested along the EmX route (public roadway), it successfully went through complete system testing at the test track in the LTD maintenance yard to ensure that the VAA system had achieved the minimum required performance in the EmX corridor (i.e., not touching any curbs or platform) and was sufficiently reliable with all the basic safety measures in place. This section includes system testing results for the test track at LTD's maintenance yard and along LTD's Franklin EmX BRT route (without passengers).

System Tests at Test Track in LTD Maintenance Yard

System testing at the LTD test track included performance testing and safety testing. As illustrated in Figure 5-9, the LTD yard track includes replicas of two docking curves—eastbound Agate and Walnut stations, the two most difficult stations for docking maneuvers. Performance testing evaluated the performance of lane-keeping, precision docking, and transitions between manual operation and automated guidance. Safety testing involved an extensive fault testing for validating fault detection and management. The standard fault testing suite included 47 different fault scenarios and their combinations.[11] These basic fault scenarios included failures for each component, subsystem, power, communication, and VAA system and subsystem functions.

[11]A total of 8 for magnetic sensor failures, 7 for steering actuator failures, 4 for yaw rate failures, 8 for CAN, 9 for control computers, 7 for operational or procedure faults, and 2 for EmX operational problems.

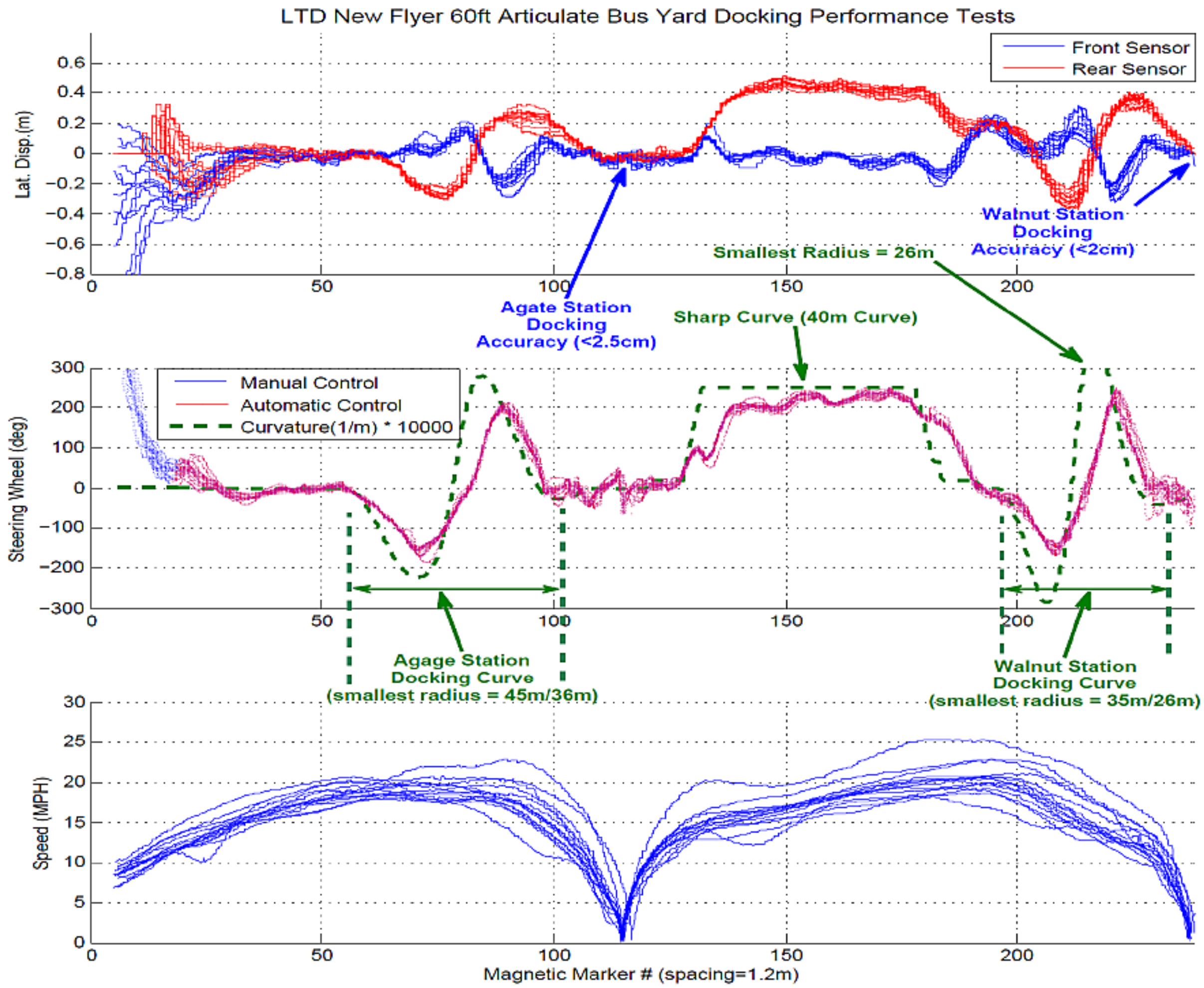


Figure 5-9

VAA lane-keeping and docking performance at LTD yard test track

Lane-keeping and Precision Docking

Figure 5-10 shows the lane-keeping and precision docking performance based on 12 consecutive test runs (on November 15, 2012) at the LTD yard track. The X axis represents the travel distance using the sequence number of the magnet markers. The top subplot shows the lateral deviation measured by the front and rear magnetometer sensors. The middle subplot shows the steering wheel angle (in magenta [when in automation] and blue [when in manual driving] lines) and the road curvature (in green dashed line). The bottom subplot shows the vehicle speed for each run.

The entry curve of the simulated EB Agate Station docking starts at marker 55 and ends at marker 102. The bus started the sharp docking curve (a 2-lane lane change with smallest radii of +45 m and -36 m) at speeds above 20 mph and sometimes at or above 20 mph until it reached the simulated platform. The VAA-controlled bus then drove along the platform (within 5 cm), often at speeds above 15 mph, and finally stopped straight (front and back ends) along the platform at marker 115. The total travel distance along the platform was less than the full length of the articulated bus (18 m). The docking accuracy was within 2.5 cm of the Agate Station platform edge.

The automated bus then maneuvered through a 90-deg sharp curve with a radius of 40 m and then immediately entered the EB Walnut Station docking curve. This docking curve is the sharpest among all the docking curves on the EmX route. The 60-ft articulated automated bus needed to complete a sharp lane change (with radii of 35 m and 26 m) and stop straight alongside the platform within 2.5 lengths of the articulated bus. In addition, as shown in Figure 5 10, the bus speeds could reach 22 mph in the middle of the lane change (large steering rate). Despite the variations in vehicle speeds, the lateral deviations of the bus remained very consistent from run to run, and the docking accuracy achieved was better than ±2 cm.

Automated and Manual Transitions

Figure 5-10 shows the data during a test run in which the driver frequently engaged and then overrode the automation. The top subplot shows the LED and sound status. The green and blue dots indicate that that the bus is under manual control and automated control, respectively. The red and blue lines at the bottom indicate that the driver engaged the automated control by pushing the AUTO switch and that the driver overrode the automation by turning the steering wheel, respectively. The middle subplot shows the lateral deviation from the magnet track as measured by the front and rear sensors. The bottom subplot shows the steering angle of the steering wheel, the curvature of the track, and the AUTO switch status and flag indicating override detections. The bottom subplot shows the vehicle speed.

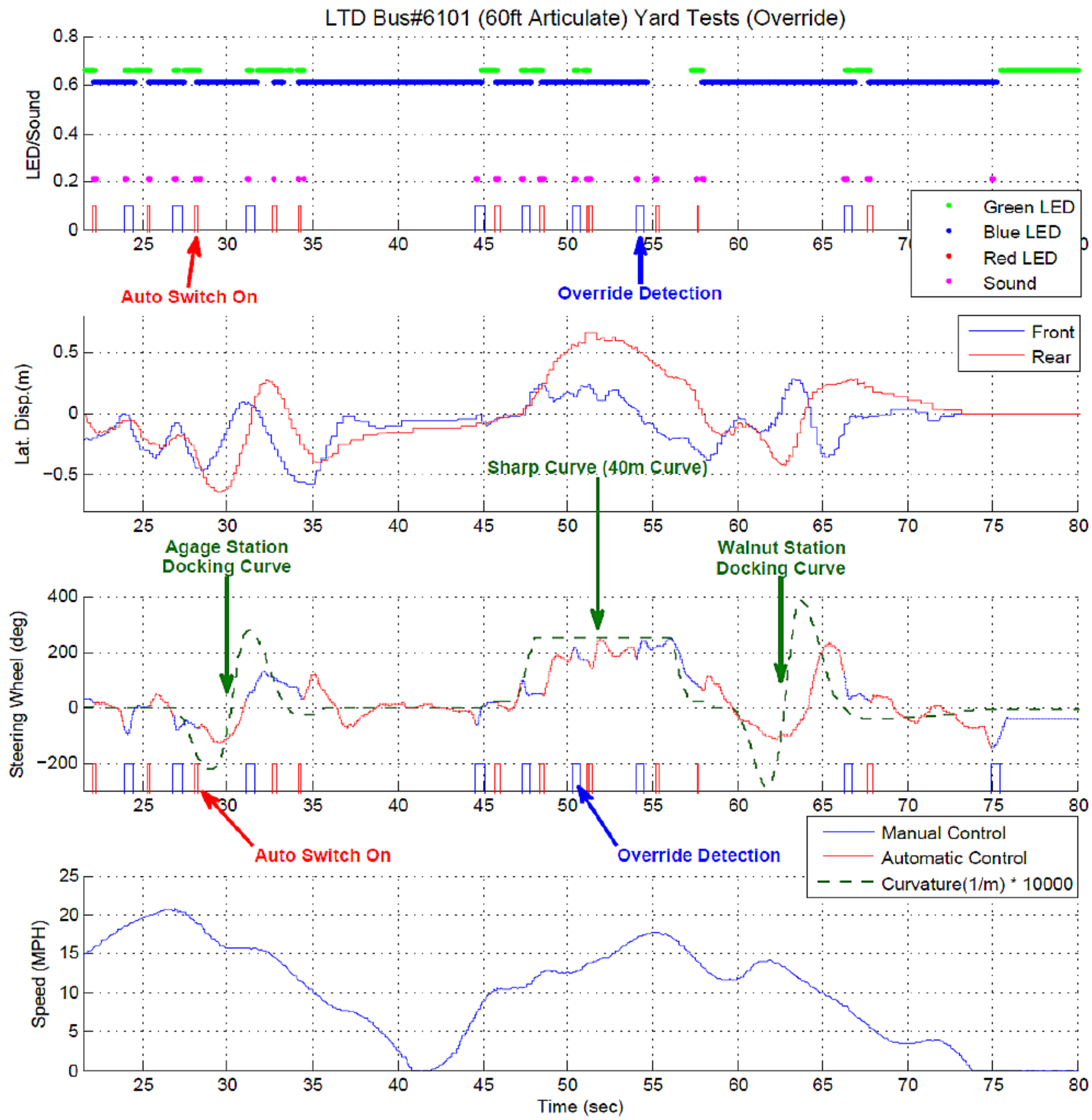


Figure 5-10

VAA system automated–manual transitions using override (LTD yard)

The segments during which the bus was under automation are marked by blue (top subplot) and red in the steering angle (third subplot). The steering angle in the third subplot shows that the steering wheel angle during manual to auto transitions was typically smoother than that during the driver's override actions. The magnetometer sensor measurements in the second subplot further verify that the vehicle moved smoothly and the automatic steering control started to bring the bus toward the road center as soon as it was engaged. Note that the bus had much larger lateral deviations when compared with those shown in Figure 5-11. The larger lateral deviation is because the bus typically was steered away from the lane center when the driver overrode the automation and much of the transition occurred on the sharp curve. Moreover, despite the large lateral deviations when the system was engaged in the middle of the sharp docking curve, the VAA system still successfully performed precision docking at the station, as shown in the second subplot.

Fault Detection and Management

Figures 5-11, 5-12, and 5-13 show the data collected during three fault testing runs conducted at the LTD yard test track. Faults were created by shutting down the power of the front and rear sensors (Figure 5 11) using the fault-injecting software in the control computers (Figure 5 12), and shutting down the active control computer (Figure 5 13). In each figure, the top subplot shows the LED status, the second subplot shows the fault detection flags and vehicle speed, the third subplot shows the lateral deviation measured by the front and rear sensors and the lateral deviation estimated by the observer, and the bottom subplot shows the actual steering angle, the steering angle commands from both control computers, and a flag indicating which control computer is the primary control computer (whose steering command is actually used to perform the automated control functions).

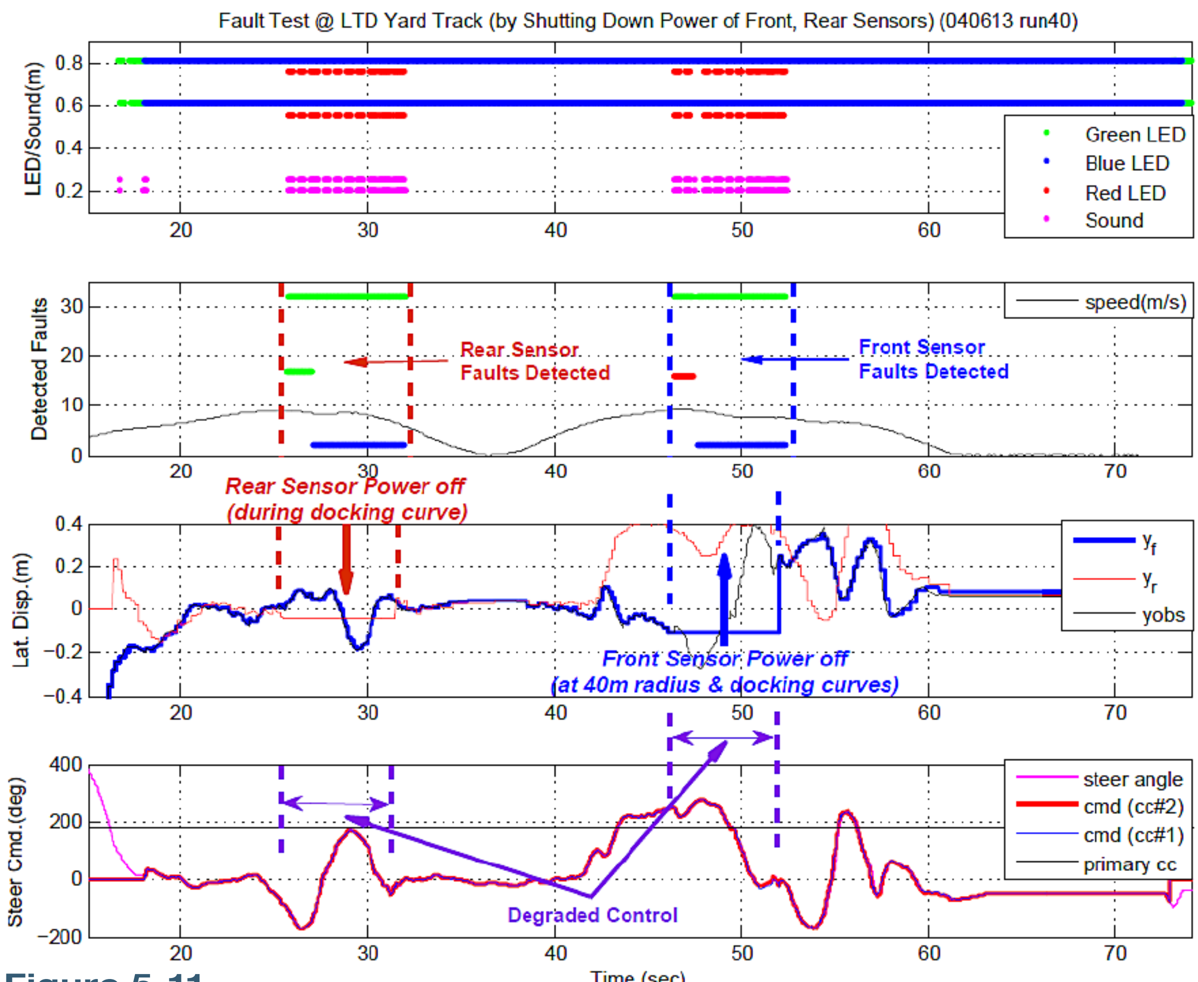


Figure 5-11

Fault testing at LTD yard track—fault in rear and front sensors (degraded control set to continuously sustain automated functions)

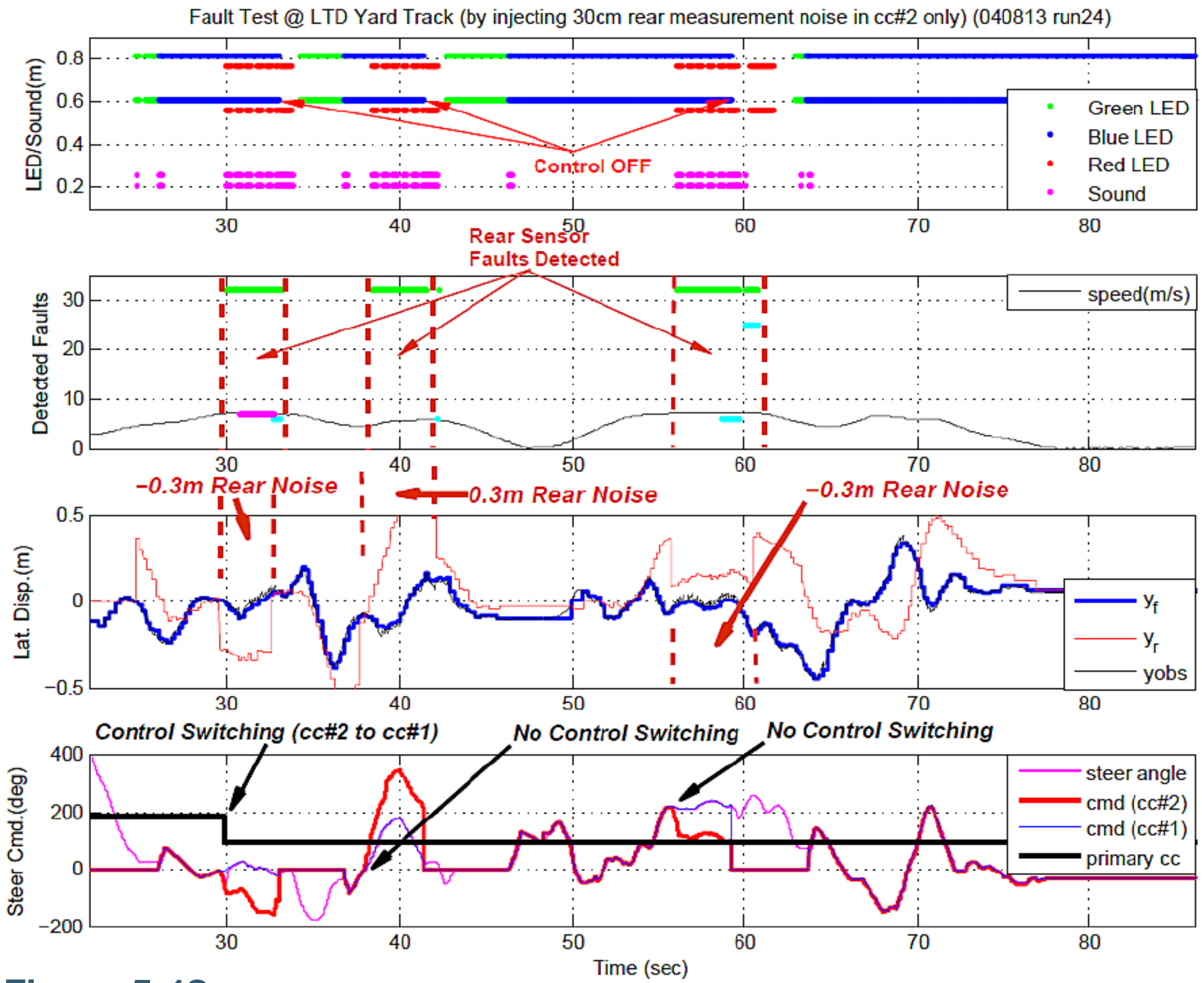


Figure 5-12

Fault testing at LTD yard track—fault in rear sensor (injecting rear sensor measurement noise into one control computer only)

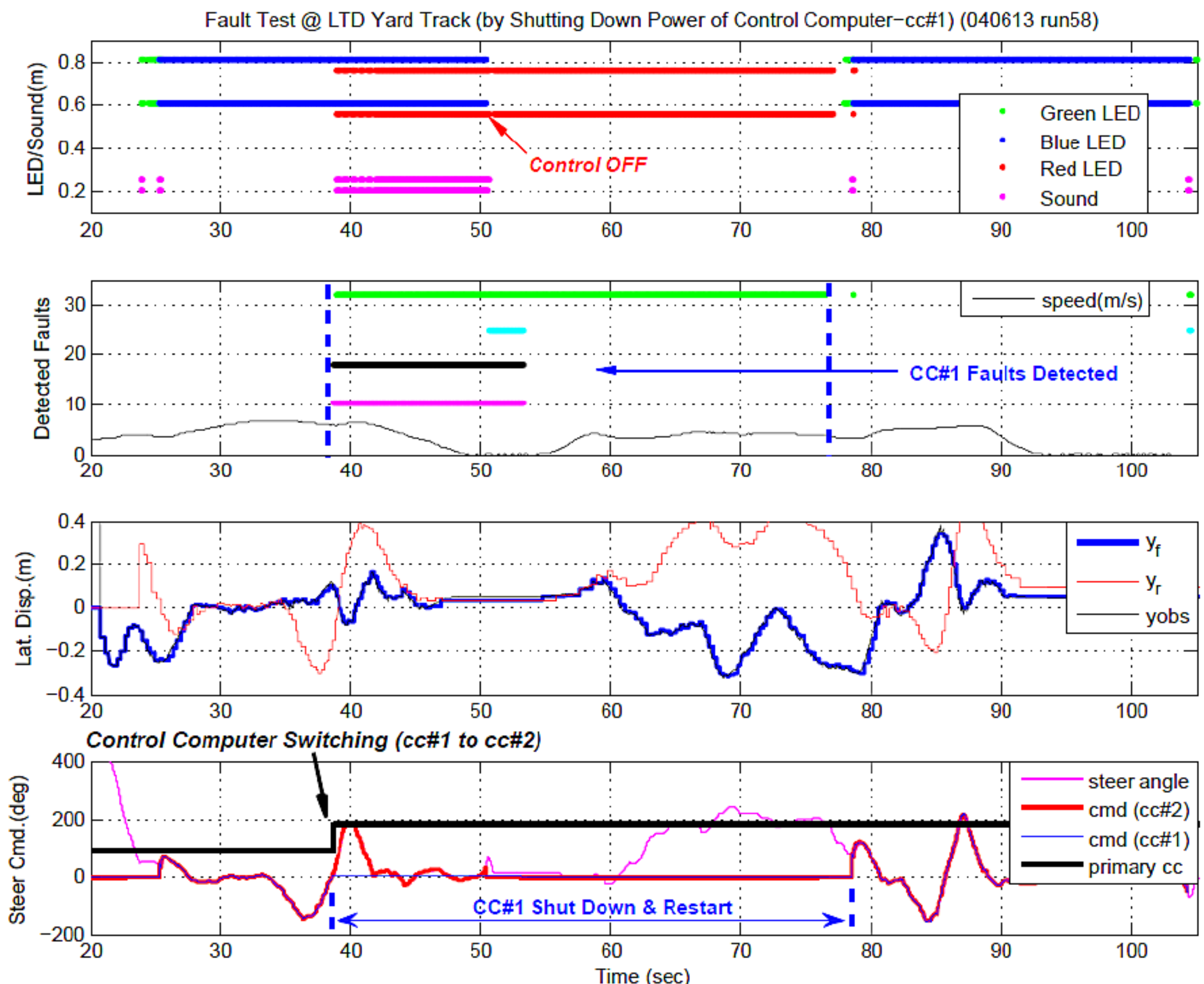


Figure 5-13

Fault testing at LTD yard track—fault in control computer (faults in shutting down one control computer)

In the test run shown in Figure 5-11, a researcher first turned off the power of the rear sensor bar in the middle of the first docking curve (to the simulated Agate Station) for about 5 seconds before turning it back on. He then turned off the front sensor bar around the end of a 40-m sharp curve and turned it back on after the second docking curve started (to the simulated Walnut Station). Both shut-downs occurred when the bus was at speed above 20 mph. The sensor measurements in the bottom subplot show that the rear and front sensor bars were turned off at 25.6 s and 46.29 s, respectively. The second subplot indicates that the first of the several faults detected for the rear and front bar failure were reported at 25.7 s and 46.38 s, respectively. Accordingly, the top subplot shows that the first warning beep started at 25.72 s and 46.4 s, respectively. The warning started within 0.1 s of shutting down the power of either the front or rear sensors. The bottom subplot illustrates that the degraded controller was very effective throughout the period of either the front or the rear sensor bar failure. Since the faults were not in either control computer (cc), no switching between the two occurred, and the primary control computer remained to be cc#2, as shown in the bottom subplot. During this test, the driver was instructed to put his hands on the steering wheel but not to override so the effectiveness of the degraded controller could be examined.

Figure 5-12 shows the data of another test run in which the software in the primary control computer[12] (cc#2, selected by the researcher at the beginning of this fault testing) injected an offset noise of -0.3 m, 0.3 m, and -0.3 m to the measurements of the rear magnetometer sensors at the times of 29.57 s, 37.72 s, and 55.73 s, respectively (shown in the third subplot). This noise was injected without any awareness of any other part of the system software. The second subplot indicates that the first detection of the fault after it was injected occurred at 29.95 s, 38.15 s, and 56.1 s, respectively, for each of the three noise injection incidents. The top subplot shows that the first warning beep started at 29.95 s, 38.2 s, and 56.1 s respectively. All these detection and warnings began at about 0.4 s after the injection of the rear sensor noises. The speed of the fault detection was designed to match the impact of the failure, and the rear sensor noise injection apparently did not create an immediate hazardous situation (based on the resulting differences in the steering command, as shown in the last subplot). The bottom subplot illustrates another major system failure response. First, the primary controller was correctly and successfully switched from cc#2 to cc#1 at 29.9 s (before the system issued first warning beep). As the steering actuator was designed to execute the steering commands from the primary controller, the steering angle then followed the commands from cc#1, which is not faulty; cc#1 remained the active controller correctly for the next two fault detections because the faulty control computer (cc#2) was not the active controller at the time. During this fault test, the driver took over steering control several seconds after the warning started.

Figure 5-13 illustrates a test run in which the primary control computer (cc#1) was suddenly shut down by the researcher without notifying the driver at 38.55 s (as shown by the stop of the steering command from cc#1 in the fourth subplot). The fault was detected by cc#2 at 38.65 s, and the primary control authority was correctly switched to cc#2 at 38.65 s. The steering actuator then executed the steering commands from cc#2 and successfully performed the lane-keeping and precision docking functions.

In summary, the extensive fault testing at the LTD yard track demonstrated that 1) all faults were quickly detected, and most faults were detected by multiple detection mechanisms; 2) all transitions were seamless, including the one

[12]The primary control computer is defined to be the control computer that is actively controlling the steering function of the bus, either cc#1 or cc#2. This was true when conducting the fault testing. For example, whenever cc#1 had fault and cc#2 had no fault, cc#2 would become the primary control computer from that time on until cc#2 became faulty and cc#1 had recovered from the fault. At that time, the primary control computer would then be switched to cc#1 again.

between the two control computers; and 3) the driver could easily take over control within a few seconds after the warning started.

System Testing at LTD's Franklin EmX BRT Route

The system testing on the LTD Franklin EmX BRT route included performance testing and safety testing. Performance testing evaluated the performance of lane-keeping and precision docking. The purpose of safety testing was to perform final validation of the fault detection and management functions that had been extensively tested in the yard track. Since the system testing was conducted on a public roadway, yard tests were conducted between system testings on the EmX route to verify any software changes made during this system testing phase.

Lane-keeping

One major advantage of VAA systems is their capability in maintaining vehicles in narrow pathways so lane width and, thus, infrastructure use and costs can be proportionally reduced. The segment of the EmX route for the VAA application consists of mostly a dedicated lane with a curb barrier where the bus lanes are 10 ft wide. Therefore, the EmX route provided an ideal case for demonstrating VAA's lane-keeping capabilities and its advantages on narrow pathways.

In addition to its narrow lane width, the EmX Route is also quite curvy, making it challenging for VAA applications. In addition to the sharp docking curves into and out of stations, the WB VAA-equipped section of the route consists of 19 curves, and the EB VAA-equipped section consists of 17 curves. The radii range from 46.6 m to 1007.6 m, with 8 curves of radius smaller than 100 m. At some locations, a 60-ft articulated bus needs to be "reverse" steered so as to maneuver along the curves without touching the curbs (a challenge for drivers).

The VAA system was initially designed to follow the magnet track with higher precision. The initial system achieved relatively small lateral deviations (with lateral positions of about 5 cm standard deviations). A demonstration run was made in July 2012;, and drivers and some passengers who stood close to the front of the bus experienced a detectable jerky ride. The main reason for the jerkiness was that the tight lane-keeping control (for rail-like performance) requires the bus to be more responsive to the track (i.e., rails). The segment between Walnut Station and Dad's Gate Station on the EmX BRT route consists of multiple curves with radii ranging from 60 m to 200 m. To achieve higher precision on such a curvy route, the steering control needed to make corrections constantly. That is, a "tight" controller results in an automated bus very much like a train, and a train negotiating tight curves at higher speeds inevitably creates larger jerks. As a comparison, when drivers drive on curvy routes, they typically tolerate relatively large deviations on curves to have a smoother ride. Therefore, relaxing the controller around tight curves becomes necessary for a smoother ride. Thus, to achieve a balance between lane-following accuracy and ride comfort on such a curvy route, the VAA system was re-tuned to tolerate larger lateral deviations.

Figure 5-14 shows the lane-keeping and precision docking performance based on 12 consecutive test runs (in April 2013) on the EmX corridor in the WB direction. The lateral positions are plotted against their corresponding magnet marker number. These lateral positions were the recorded measurements from the front magnetometer sensors whenever a magnet marker was detected. The top subplot shows the lateral positions from the front magnetometer sensors; the major intersections along this EmX corridor are also marked. The middle subplot shows the steering wheel angle and the corresponding road curvature; the steering angles in blue were under manual control and those in red corresponded to the automated steering control. The bottom subplot shows the bus speed.

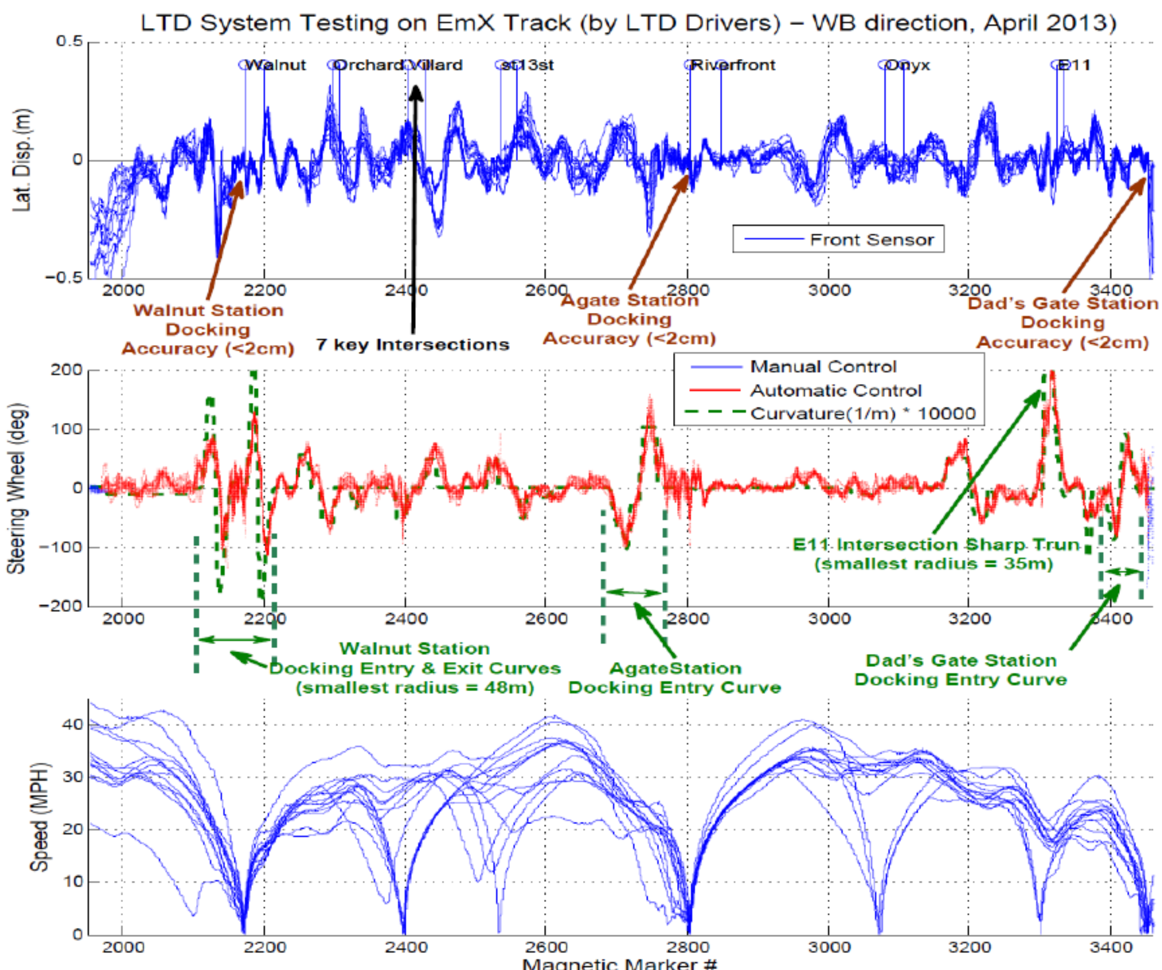


Figure 5-14

Lane-keeping performance at EmX track (WB direction)

As shown in the top subplot, most of the larger tracking errors (~20 cm) occurred at sharp curves (mostly docking curves), and the tracking errors were generally smaller than 10 cm at the straighter sections of the road. The second subplot illustrates that the steering wheel exceeded 50 deg on the WB track 16 times on the WB direction. In addition, the largest steering angle could reach above 230 deg at the E11 turn. The speeds in the bottom subplot demonstrate that speed variations were very large in this narrow corridor, and speeds exceeded 40 mph several times during testing. The small radii, the large variations of speed, and the narrow lane all contributed to the difficulty of automated control. The resulting standard deviation of the tracking error, excluding the docking entry and exit curves, was 7.9 cm.

Figure 5-15 displays the lane-keeping and precision docking performance based on 12 consecutive test runs (in April 2013) at the EmX corridor in the EB direction. Similar to the WB direction, the top subplot shows that most of the larger tracking errors (~20 cm) occurred at sharp curves (mostly docking curves), and the tracking errors were generally smaller than 10 cm at the straighter sections of the road. The second subplot shows that the steering wheel exceeded 50 deg on the EB track 17 times on the EB direction. In addition, the steering angle could reach above 150 deg 5 times. The speeds demonstrated that speed variations were very large in this narrow corridor, and the speed exceeded 40 mph at times during the testing. The resulting standard deviation of the tracking error, excluding the docking entry and exit curves, was 7.2 cm, despite the small radii and the large variations of speeds.

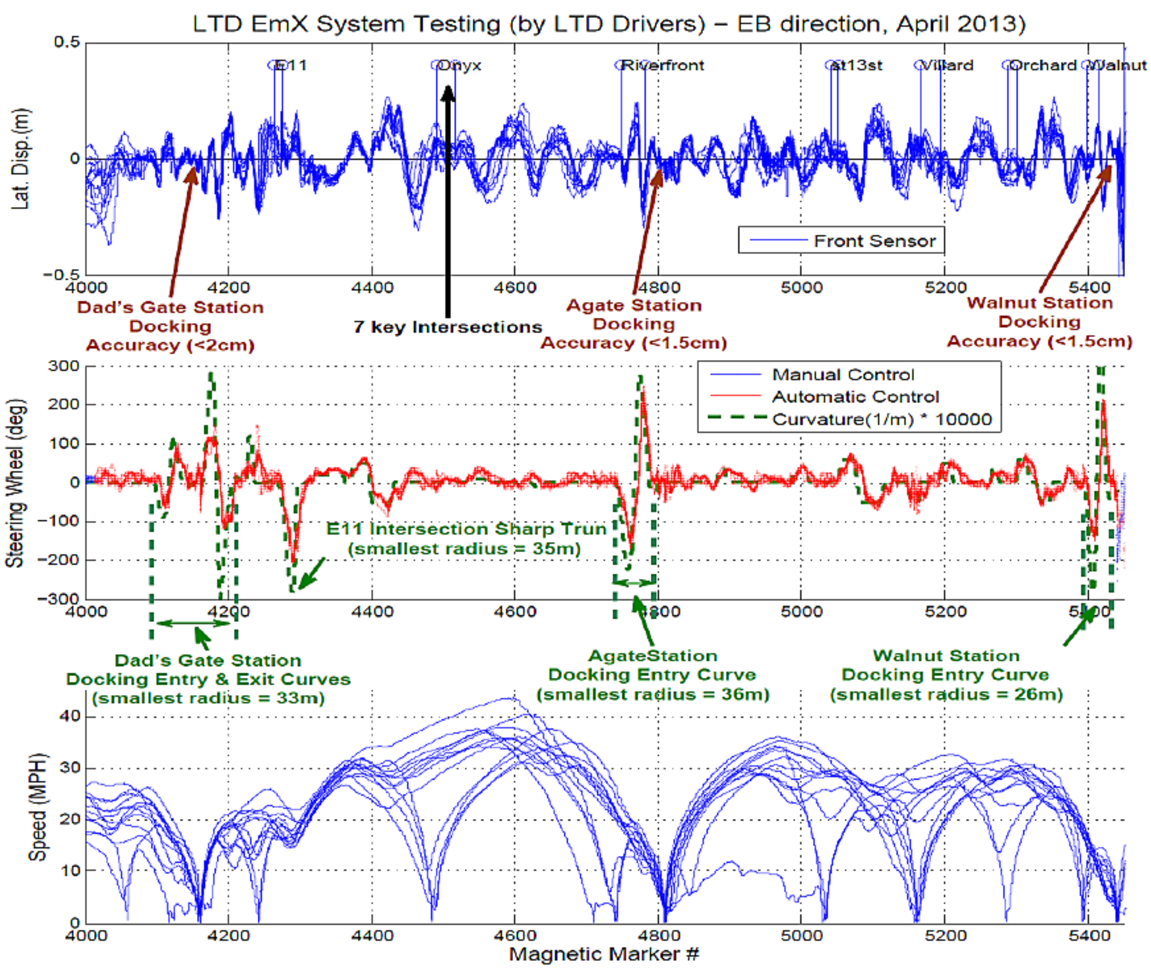


Figure 5-15

Lane-keeping performance at EmX track (EB direction)

Precision Docking

Three stations along LTD's Franklin EmX BRT route were selected for the VAA application: Walnut Station, Agate Station, and Dad's Gate Station. Each station contains two docking platforms—one WB and one EB. Figures 5-16, 5-17, and 5-18 show aerial views of the stations.

Figure 5-16

Walnut Station (bus traveling in WB direction, right to left)

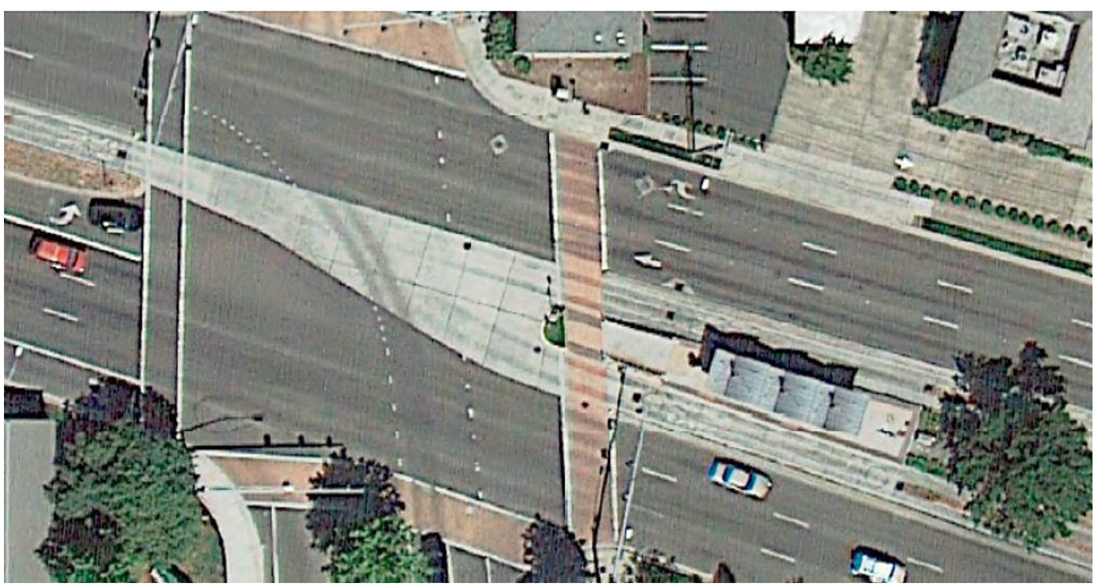


Figure 5-17

Agate Station

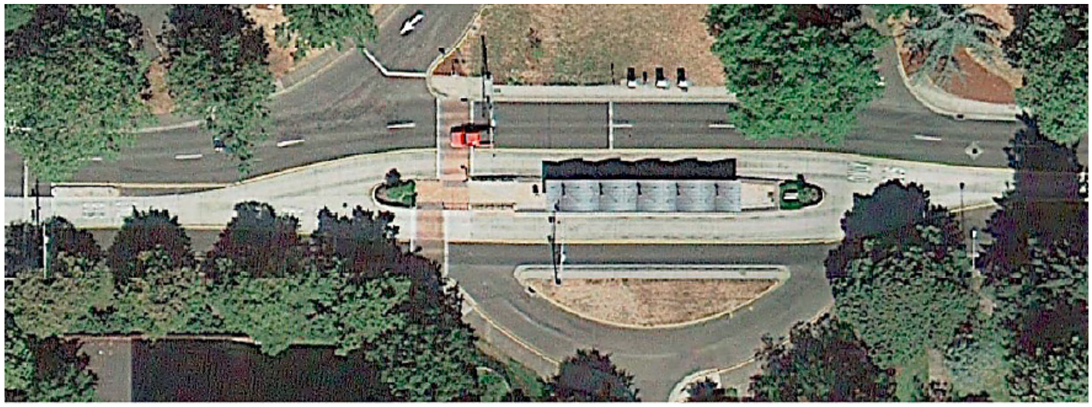


Figure 5-18

Dad's Gate Station

Some curves entering a station are challenging for the New Flyer 60-ft articulated bus. For example, the docking at the Walnut Station in the EB direction (left to right in Figure 5-16) requires the 60-ft bus to complete a full lane change within a 160-ft longitudinal distance. The docking at Agate Station in the EB direction (left to right in Figure 5-17) requires the 60-ft bus to move about 26 ft laterally (more than making two lane changes) within a 223-ft longitudinal distance. In addition, since the roadway widths range from 9 ft to 14 ft at stations, vehicles have a very narrow area to pull up to the stations.

Based on the legal performance requirements from the ADA, the requirement for the horizontal gap between a station platform edge and vehicle floor, measured when the vehicle is at rest, must be no greater than 7.62 cm (3 in.). For the VAA project, the target horizontal gap for precision docking was set to 4 cm. Since LTD placed guard strips along the platforms to reduce damage to buses and station platforms during manual docking, the horizontal gap was between the guard strips and the vehicle floor.

Based on the same 12 round-trip automated VAA runs noted in the previous section, Figures 5-19, 5-20, and 5-21 show the precision docking performance for the three stations in both directions (left figures for WB, right figures for EB). The top subplots depict the measurements from the front and rear sensor bars, the middle subplots show the steering angle and the track curvature, and the bottom subplots show the speeds of the bus (controlled by the operator). These plots exhibit clearly that the docking accuracies for all stations were within +-2 cm (for both the front and rear measurements at the time of docking) to the desired lateral positions (STD < 1 cm) for either the very sharp (25–35 m radius) or the relatively mild (~100 m radius) docking curves.

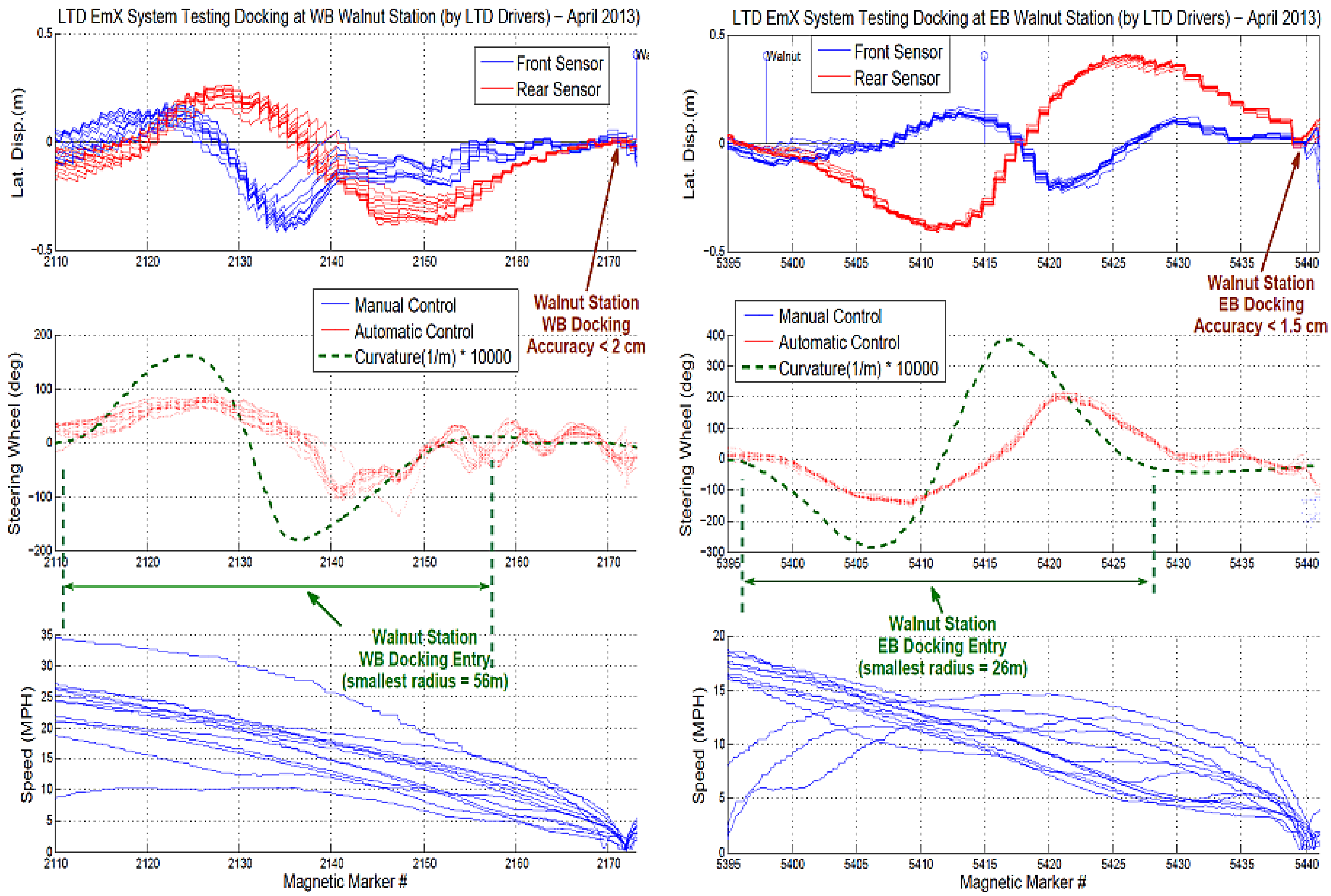


Figure 5-19

Precision docking performance at EmX track—Walnut Station (WB & EB)

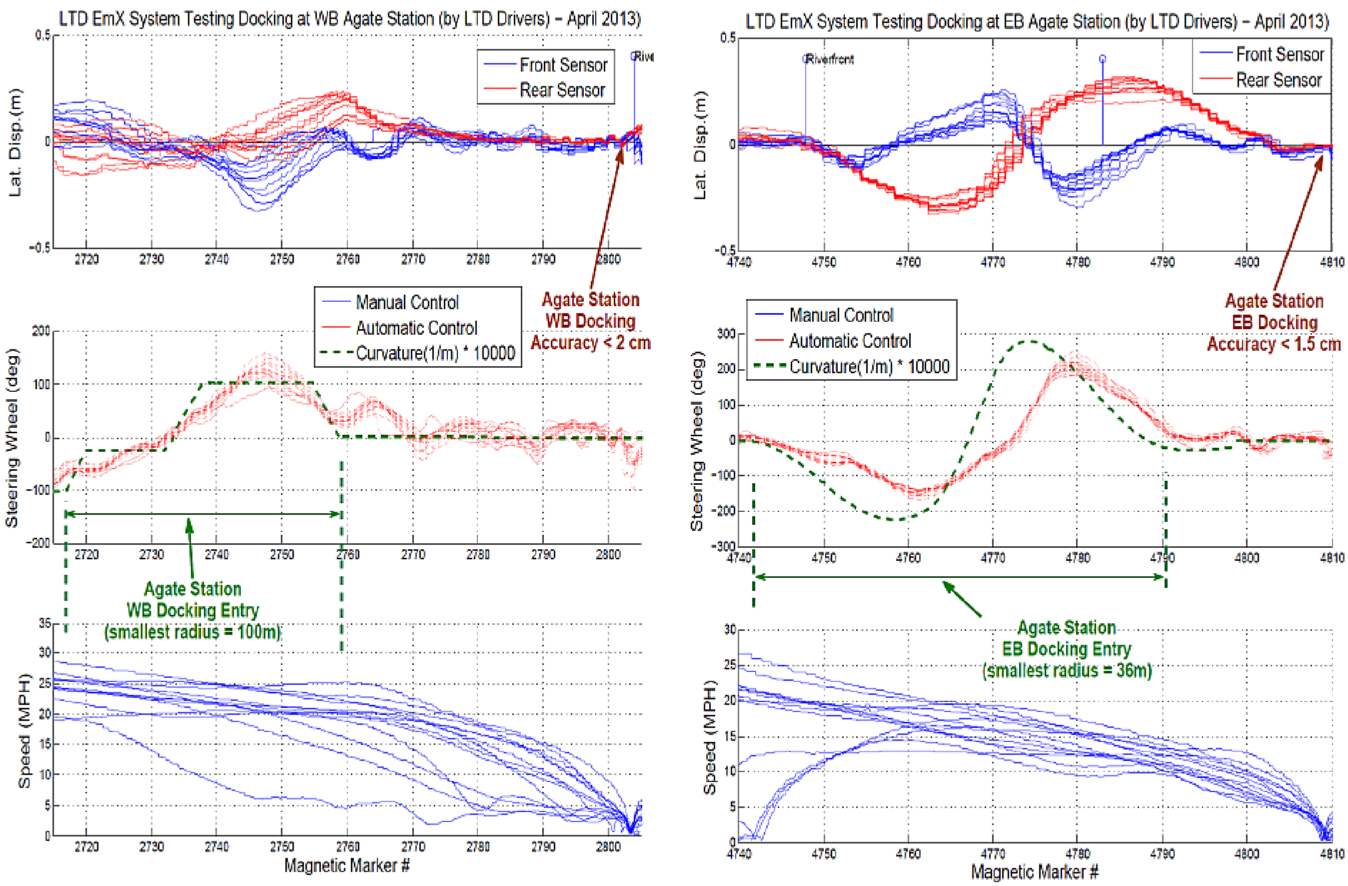


Figure 5-20

Precision docking performance at EmX track—Agate Station (WB & EB)

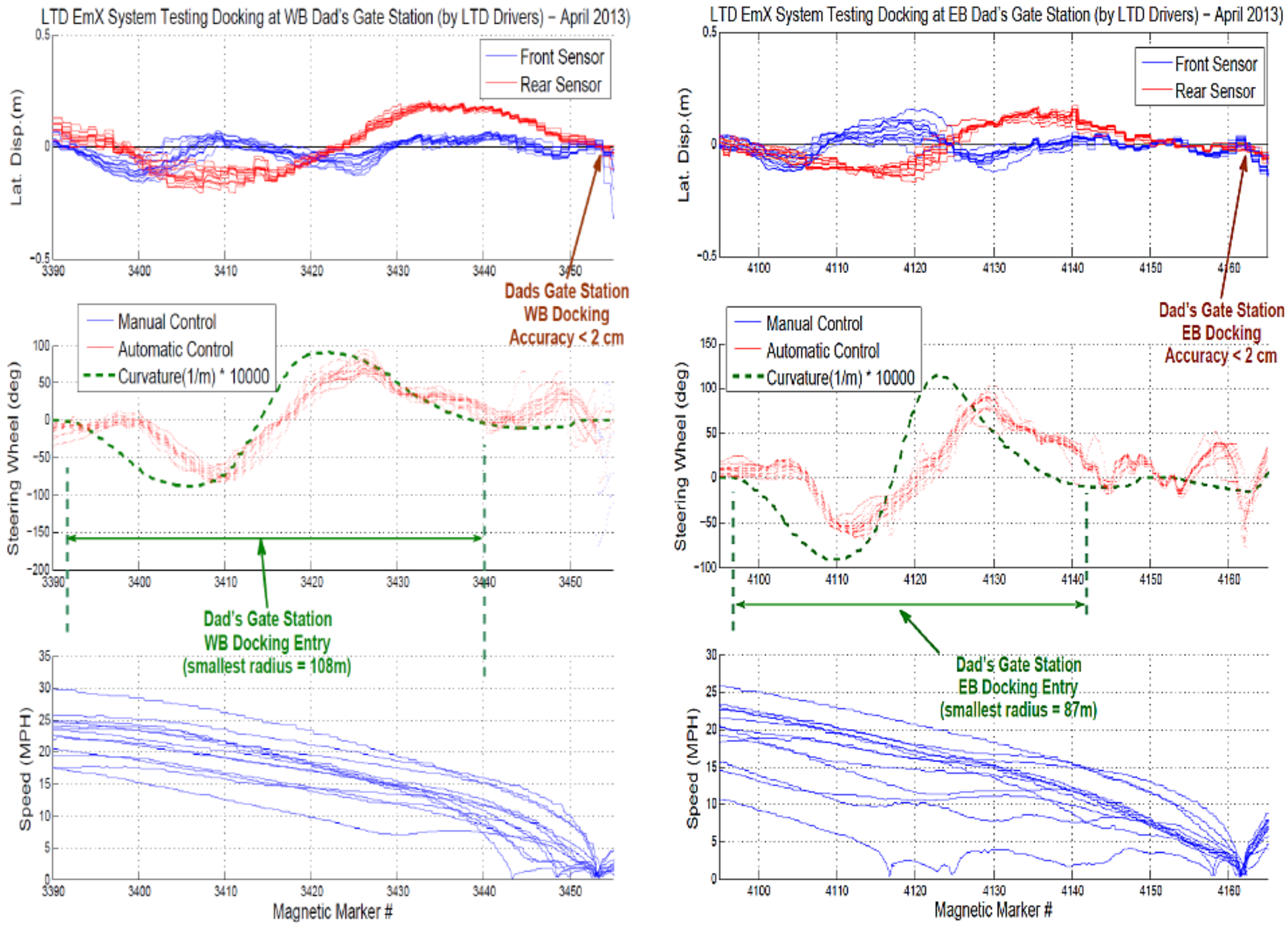


Figure 5-21

Precision docking performance at EmX track—Dad's Gate Station (WB & EB)

For the 12 test runs, the maximum recorded speeds from starting the docking entry curve to when the bus front tire reached the platform (at the end of the curve) were as follows:

- Walnut Station: WB: 35 to 17 mph, EB: 19 to 12 mph
- Agate Station: WB: 31 to 25 mph, EB: 26 to 15 mph
- Dad's Gate Station: WB: 30 to 17 mph, EB: 25 to 17 mph

In addition, the corresponding smallest radii of curvature of the docking curves were:

- Walnut Station: WB: 56 m, EB: 26 m
- Agate Station: WB: 100 m, EB: 36 m
- Dad's Gate Station: WB: 108 m, EB: 87 m

The performance of the steering controller was tested when the bus was maneuvering along the sharp docking curves at high speeds while maintaining high docking accuracy along the station platform. The bus (including its tires) never made contact with the platform or the guard strips.

Fault Testing

As the final validation of safety and fault testing, several basic fault scenarios (shutting down power to components by trainers/instructors) were tested along the EmX corridor with the LTD drivers. These fault tests eventually became part of the formal driver training procedure conducted by the LTD VAA instructors. Figure 5-22 shows the data collected during a fault testing conducted by an LTD operator along the EmX track. The faults were created by shutting down the power of the front and rear sensors, primary (active) control computer, and actuator. The top subplot shows the LED status, the second subplot shows the fault detection flags and vehicle speed, the third subplot plots the lateral deviation measured by the front and rear sensors and the lateral deviation estimated by the observer, and the bottom subplot shows the actual steering angle, the steering angle commands from both control computers, and a flag indicating which control computer was the primary control computer.

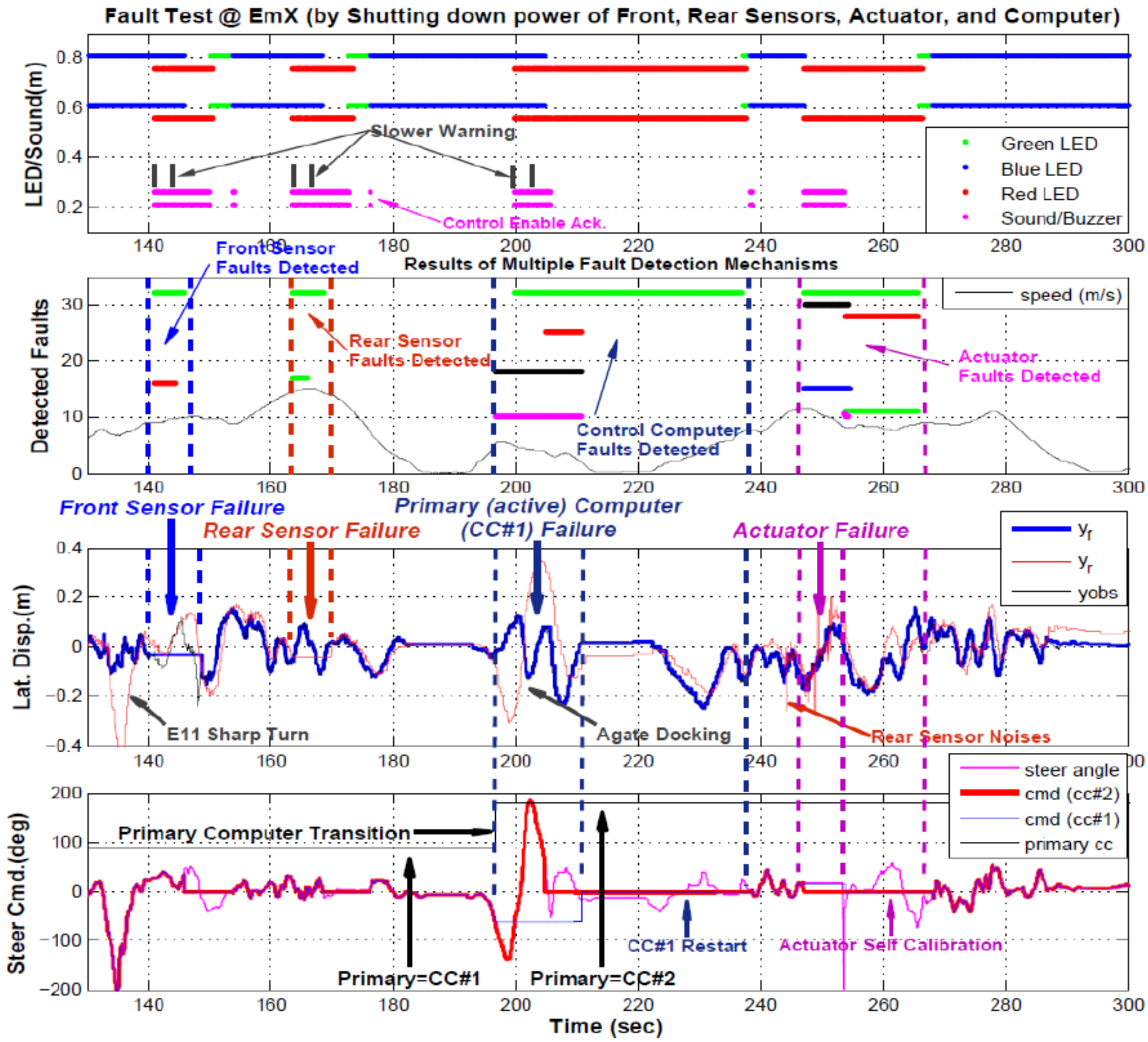


Figure 5-22

Fault testing on EmX conducted by LTD instructors

The fault testing at the EmX route confirmed that 1) all faults were quickly detected and each fault was detected by multiple detection mechanisms; 2) all control transitions were seamless, including the one between the two control computers; and 3) the driver easily took over the control within a few seconds after the warning started. Only the actuator power-off fault triggered an immediate warning.

System Test Results: VAA Application at AC Transit

This section presents the results from the system testing at the RFS test track for the AC Transit M Line VAA applications. Due to delays from contractual issues, in the end, the system and operational tests for the M Line along the SR 92 HOV lane and tool plaza were not conducted.

System Testing at the Test Track at RFS

System testing at the RFS test track included performance testing and safety testing. Performance testing evaluated the performance of lane-keeping, precision docking,[13] and transitions between manual operation and automated control. The safety testing involved an extensive fault testing for validating the fault detection and management functions.

Lane-keeping and Precision Docking

Figure 5-23 shows the lane-keeping and precision docking performance test results based on 10 test runs at the RFS test track. The X axis represents the travel distance using the sequence number of the magnet markers. The top subplot shows the lateral deviation measured by the front and rear magnetometer sensors. The middle subplot shows the steering wheel angle (magenta when in automation and blue when in manual driving) and road curvature (green dashed line). The bottom subplot shows the vehicle speed for each run.

[13]Precision docking, especially S-curve precision docking, requires a steering control system to achieve high-accuracy performance consistently. It is a much more challenging maneuver than typical lane-keeping. Although the AC Transit applications did not include precision docking, testing the control system's capability of precision docking helped ensure that the control system could maintain high-accuracy performance in almost all conditions on the HOV lane.

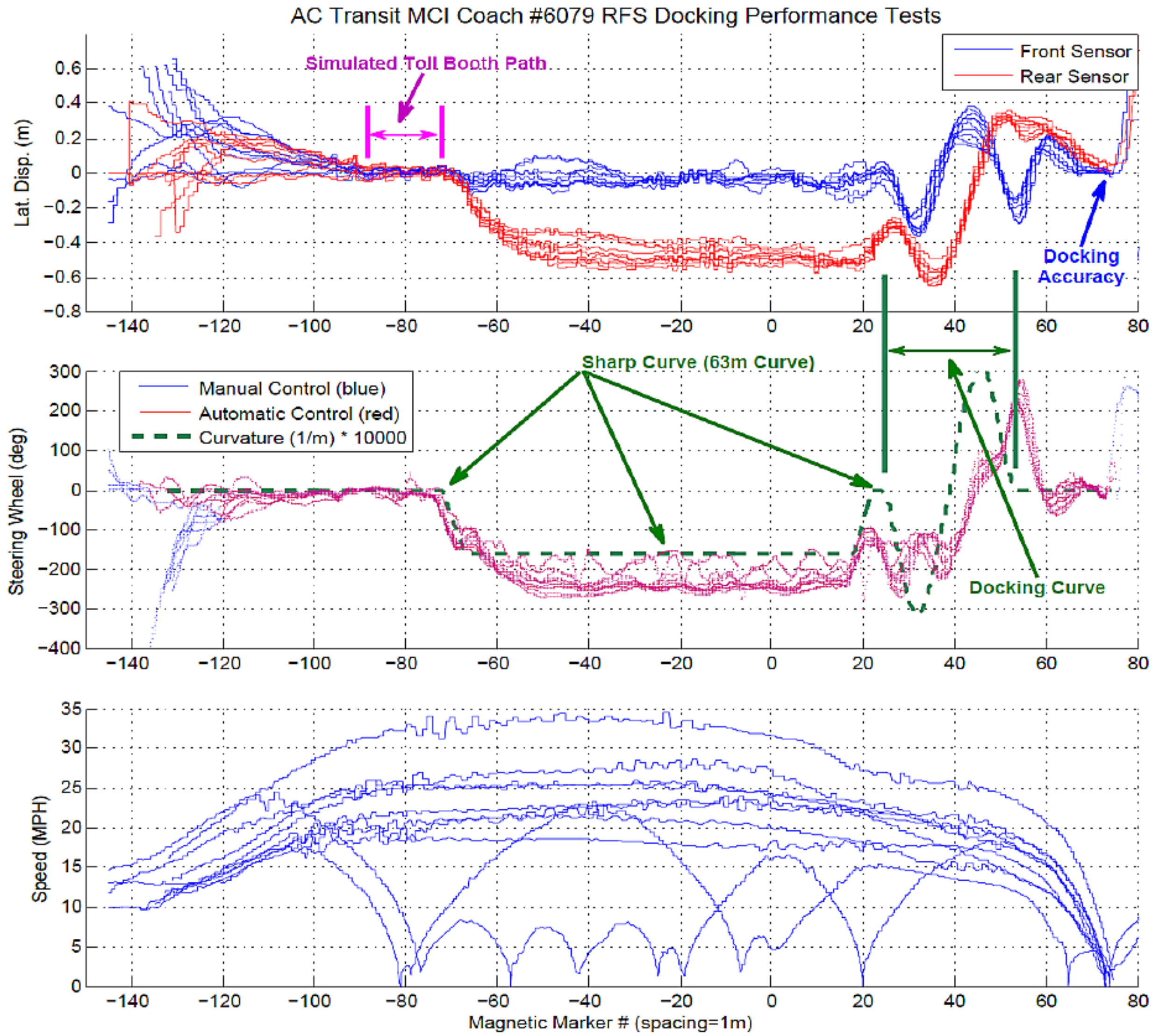


Figure 5-23

VAA lane-keeping and docking performance at RFS test track

As shown in Figure 5-23, the VAA system kept the bus almost right at the center of the lane (better than 10 cm) while the bus negotiated the sharp curve (with a radius of 63 m) between marker -70 and marker 20.[14] Despite variations in vehicle speeds (including stop and go motions), the lateral deviations of the bus remained consistent from run to run.

Moreover, to test lane-keeping maneuvers through a narrow path (such as a toll booth), the 20-m straight segment was artificially set from marker -90 to marker -70 as a narrow path. The sensor measurements showed that the bus was within 5 cm (2 in.) from the lane center at the narrow toll booth segment despite speeds varying from 0 mph to 34 mph.

The 25-m docking curve, originally designed for testing with passenger cars, is a very challenging docking curve for a 50-ft coach bus. However, the VAA system was able to consistently bring the bus straight and parallel to the platform with the lateral deviation within +/-1 cm. The sensor measurements (shown in the top subplot) verify the consistency of the docking performance. Although precision docking is not part of the operational scenario for the field operational tests on AC Transit's M Line, the data demonstrate that the VAA bus, with a significantly much larger wheel base (26 ft vs. 19 ft), achieved about the same level of precision docking performance as that achieved by the LTD bus.

Manual Driving and Automation Transitions

Figure 5-24 shows the data collection during a test run in which the driver frequently engaged and then overrode the automation. The segments during which the bus was under automation are marked. The steering angle in the middle subplot clearly shows that the steering wheel angle was smooth despite frequent manual–auto transitions. The sensor measurements in the top subplot further verify that the vehicle moved smoothly, and the automatic steering control started bringing the bus toward the road center as soon as it was engaged.

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[14]The measurements of the front magnetometer and rear magnetometer sensors were about 40–50 cm apart when the marker number is between -60 and 20. At that segment of the test track, the bus was negotiating a tight curve (radius = 63 m). Since a 50-ft coach bus is a rigid body, the radius for each point on the bus is different when it negotiates a curve. For a vehicle without rear steering capability, if the middle point of the rear axle turns at a radius of R, the middle point of the front axle then turns at a radius of the square root of (R*R + wheelbase*wheelbase). The trajectories of those two points are different. As the front and rear magnetometer sensor bars were installed at different locations of the bus, their distances to the magnet track (i.e., the road centerline) were different as well; the sharper the curve, the larger the difference based on the geometric relationship.

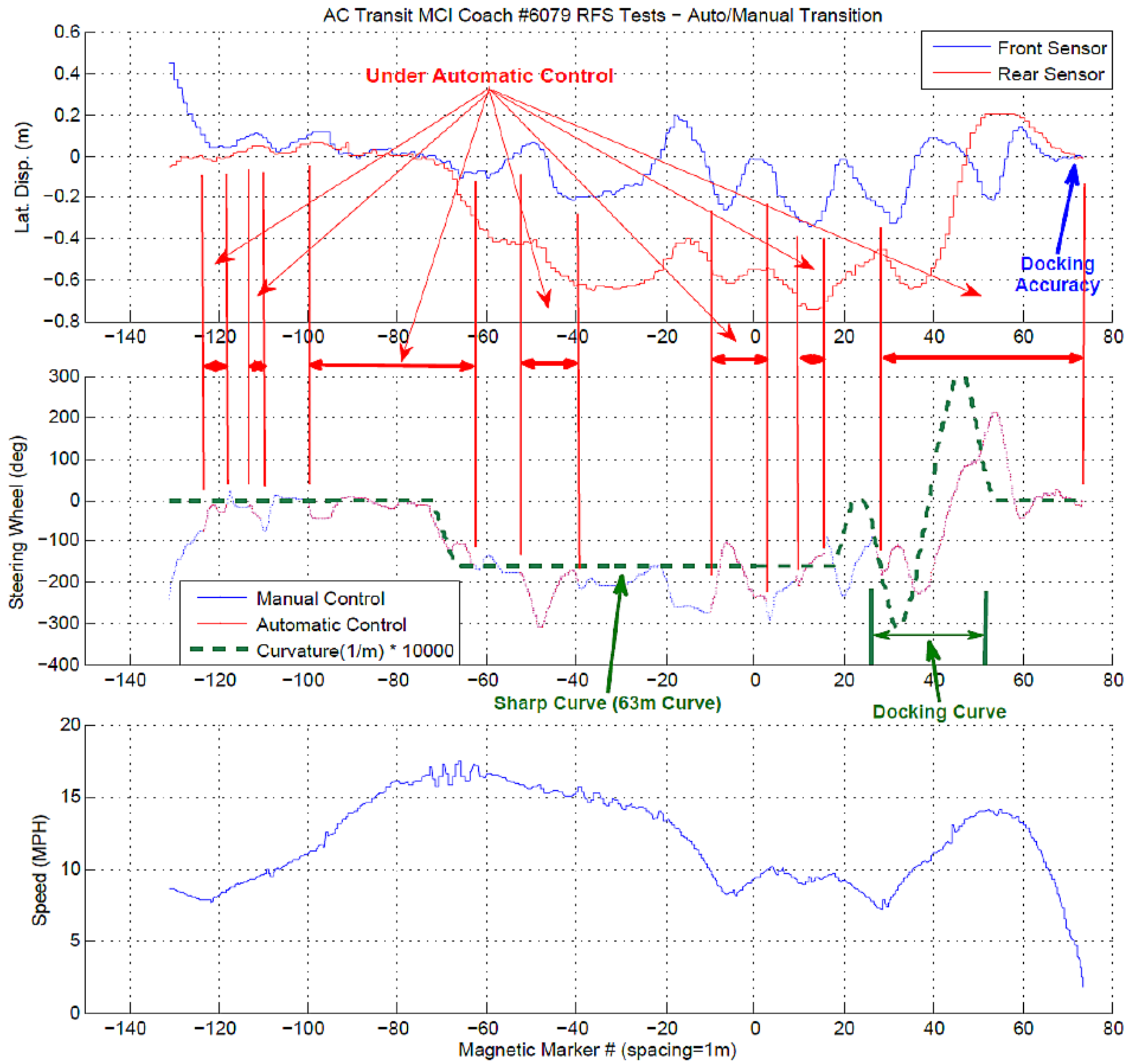

Figure 5-24

VAA system performance in manual–auto transitions

Note that the bus had much larger lateral deviations; the cause was that the bus was typically steered away from the lane center when the driver overrode the automation. However, despite the large lateral deviation when the system was engaged at the beginning of the docking curve, the VAA system still successfully performed precision docking at the station (as shown in the top subplot).

Fault Detection and Management

Figures 5-25 and 5-26 show the data collected during two fault testing runs conducted at the RFS test track. In both figures, the top subplot shows the LED status, the second subplot shows the fault detection flags and vehicle speed, the third subplot shows the lateral deviation, and the bottom subplot shows the actual steering angle, the steering angle commands from both control computers, and a flag indicating which control computer was the primary control computer.

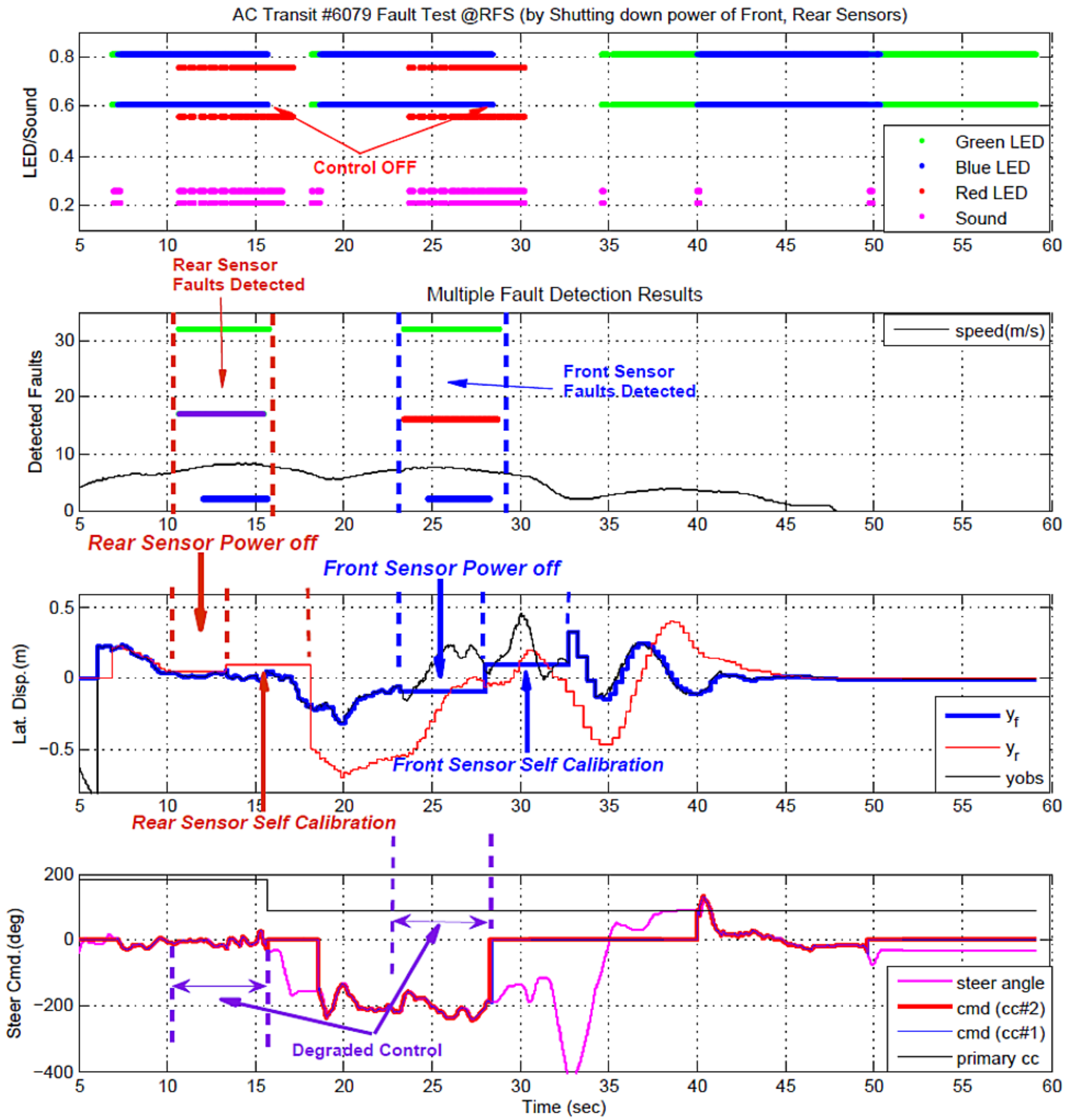

Figure 5-25

Fault testing at RFS test track—faults in front and rear sensors

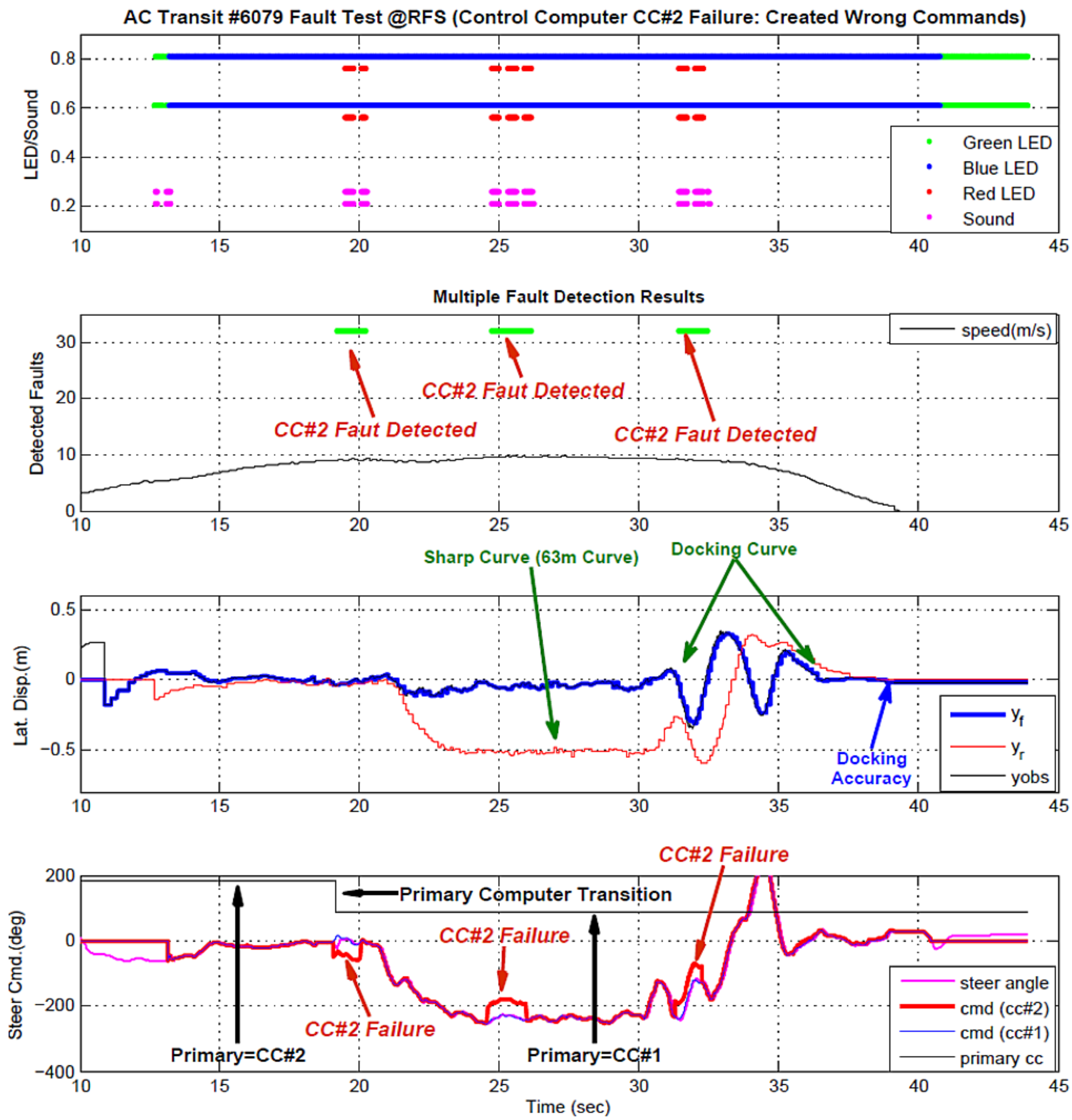

Figure 5-26

Fault testing at RFS test track—faults in control computers

In the test run shown in Figure 5-26, faults were created by shutting down the power of the rear sensor and then the front sensor. A researcher first turned off the power of the rear sensor bar in the middle of the first docking curve for about 5 seconds before turning it back on. He then turned off the front sensor bar around the end of a 63-m radius sharp turn and turned it back on in the middle of the docking curve. Both shut-downs occurred when the bus was at speed close to 18 mph. The sensor measurements in the third subplot show that the rear and front sensor bars were turned off at 10.62s and 23.27s, respectively.

The second subplot indicates that several faults detected for the rear and front bar failure were first reported at 10.71s and 23.39s, respectively. Accordingly, the warning (top subplot) started within 0.1s of the power shut-down of either the front or rear sensors. The forth subplot illustrates that the degraded controller was effective throughout the period of either the front or rear sensor bar failure. During this test, the driver was instructed to put his hand on the steering wheel but not to override so the effectiveness of the fault-tolerant control could be examined.

In the test run shown in Figure 5-26, faults were created by using the fault-injecting software in the control computers. In this fault testing, cc#2 was started as the primary control computer. A 45-deg steering command offset was suddenly injected inside cc#2 right after cc#2 determined its final steering command. The injection was programed in a way such that both control computers and the rest of the system had no knowledge of this injection. The injection was created three times and lasted a few seconds each. The first time it occurred just before entering the 63-m sharp curve, the second time in the middle of the 63-m sharp curve, and the last time in the middle of the docking curve. All occurred when the bus was at speeds above 20 mph. The steering commands in the third subplot indicate that the erroneous command issued by cc#2 started at 19.07s, 24.60s, and 31.3s, respectively. The second subplot indicates that the fault was detected each time and was first reported at 19.2s, 24.74s, and 31.43s, respectively. Accordingly, warnings (top subplot) were issued within 0.14 s of the injection of the erroneous command. Finally, the forth subplot illustrates that the primary control computer was correctly switched to be cc#1 at 19.2 s, and the primary control computer correctly remained to be cc#1 for the next two detected faults. During this test, the driver was instructed to put his hands on the steering wheel but not to override so that the effectiveness of the switching could be examined. The bus automated operation was not affected by this failure.

In both runs, 1) all faults were quickly detected, and each fault was detected by multiple detection mechanisms; 2) the observers provided the position estimation regardless of the types of the sensor failures; 3) all transitions were seamless, including those between the two control computers; and 4) the driver easily took over control within a few seconds after the warning started.

Field Operational Testing

Through collection of sufficient field data in a real-world operating environment, field operational testing of the VAA project was intended to enhance the industry's understanding of 1) potential benefits of VAA applications and technologies, 2) acceptance levels of drivers, transit operators, and customers, and 3) potential issues involved with use of VAA technologies on transit buses. Since the operational tests of this project included deploying the first automatically-steered bus in the US that carries passengers with daily service for an extensive period of time, safe operation was the most important consideration. The operational test plan was divided into two phases, VAA operation without and with passengers (revenue service operation). The exact period of time for testing VAA without passengers before proceeding to revenue service operations was determined by the transit agency based on driver responses and the safety record of operation.

To achieve these general goals, field operational tests at the AC Transit site and the LTD site aimed to provide quantitative measures of potential benefits and acceptance levels. More specifically, the operational tests should provide measures of the following potential benefits:

- Enabling buses to operate within narrow lanes to facilitate higher-quality transit systems:
  - Enabling dedicated-lane BRT deployments that would not otherwise be possible
  - Reducing construction and right-of-way costs for new transitways, especially if they involve the need for costly new tunnels or bridges
- Improving operational efficiency and saving costs for transit agencies:
  - Enabling full-speed operations in locations where drivers would otherwise need to slow down significantly, thereby improving productivity and reducing passenger delays (AC Transit)
  - Saving maintenance expenses for wheelchair ramp deployments and tires by avoiding tire scuffs against curbs during inaccurate manual docking maneuvers (LTD)
  - Eliminating the need to slow down drastically to ensure safe passage through toll plazas, saving travel time and fuel and avoiding damage to bus side mirrors (AC Transit)
- Improving customer satisfaction and motivating increases in ridership:
  - Rail-like ease of boarding and alighting at stations, with negligible gap between station platform and bus floor, by use of precision docking (LTD)
  - Smoother ride quality for high-speed driving along HOV lanes (AC Transit)
  - More reliable service and reduced trip time (LTD, AC Transit)

Both transit properties saw these field operation tests as a critical step toward more extensive use of VAA technologies on future bus routes and service.

Operational Data Collection and Analysis

Data collection and analysis were intended to support the VAA program goals through the following objectives:

- To measure operational improvements due to the introduction of VAA through quantitative technical performance of the VAA systems in real-world conditions

- To identify VAA faults that could be encountered in real-world transit operations (and their frequency of occurrence)
- To understand through both technical data and subjective reactions if VAA facilitates driver ease of operation
- To understand passenger perceptions of the VAA system
- To understand the impact of the VAA technologies on maintenance

To assess if the objectives had been met, FTA selected NBRTI to conduct an independent evaluation of the VAA demonstration.

Data to be Collected

According to VAA program goals, data relevant to program objectives needed to be collected and analyzed. The following are examples of data to be collected:

- Running (travel) time
- On-time performance
- Dwell time at stops (LTD)
- Average speed
- Speed through toll booth (AC Transit)
- Speed along curved sections (LTD)
- Vehicle "tracking path" accuracy (lateral deviation from roadway / busway center line)
- Vehicle precision docking accuracy (lateral deviation from the gap standard between the vehicle and platform edge) (LTD)
- Vehicle ride quality (lateral acceleration)
- Transit maintenance and repair data

To identify VAA faults encountered in real-world transit operations, it was necessary to record faults detected by the VAA system, including both non-critical and critical faults.

Driver perceptions and experiences provide information on whether VAA facilitates driver ease of operation. Meanwhile, focus groups help to obtain passenger perceptions.

VAA's impact on maintenance can be assessed by keeping a record of damage to and maintenance of the transit buses (including tires, mirrors, bus body, and wheelchair lifts), as well as damage to and maintenance of bus stations (e.g., signage and curb edge). Maintenance of the VAA system and components should also be recorded for the assessment.

The data to be collected was categorized into two main categories: objective data and subjective data. The objective dataset includes quantitative performance data that describe the operation of the vehicle and the VAA system, as well as data related to the operating environment and maintenance.

The subjective dataset includes qualitative perceptions and experiences of bus operators and passengers.

Objective Dataset – Quantitative Performance Data

The VAA system has an on-board data acquisition system which records measurements describing the operation of the vehicle and the VAA system. During the subsystem and system validation tests, these measurements allowed PATH researchers to monitor system performance and identify, diagnose, and fix potential problems. During the field operational tests, these measurements were recorded and analyzed for the broader assessment of VAA system performance. Data to be collected included:

- Vehicle absolute locations and time stamps (from GPS)
- Complete speed profile, including stopped time, and total travel time
- Lateral position error profiles, for both front and rear sensor locations
- Steering commands issued by VAA controller
- All steering actions (steering angle), both automatic and manual
- Initiations and terminations of automatic steering (by driver or automatic)
- Braking actions (deceleration rate)
- Lateral acceleration and yaw rate
- Consequential fault conditions identified by the VAA system's self-diagnoses

Objective Dataset – Transit Property Record Keeping

In addition to quantitative performance data, the objective dataset also included data related to the operating environment and maintenance. The data to be collected via transit properties' record keeping included the following:

- Vehicle maintenance actions for non-VAA subsystems (with special emphasis on tire and mirror damage) for all buses of the same type operating on these routes
- Maintenance actions for VAA subsystems and the time they require
- Reports of any safety incidents (crashes or passenger falls) for all buses operating on these routes, with as much detail about causes as possible
- Driver comments about any concerns about VAA performance, user interface, or apparent failures (as soon as they occur, if possible, but no later than the end of the daily run)

Subjective Dataset

The data to be collected in surveys and/or interviews included the following:

- Passengers
  - Perceived ride quality (smoothness, comfort)
  - Perceived safety

  - Trip timeliness and reliability
  - Ease and speed of boarding and alighting (LTD)
- Bus operators
  - Ease of operation
  - Perceived ride quality (smoothness, comfort)
  - Job stress
  - Perceived performance and reliability
  - Perceived changes in safety

Data Collection Mechanisms

Data Collection Instrumentation

Quantitative performance data were collected by an on-board data acquisition system that collected the data through its interface to the VAA subsystems and the vehicle's CAN data bus and recorded the data in its storage. These data were recorded at all times when the vehicle electrical system was on, without requiring any special actions by the driver or maintenance staff. Due to limited on-board storage, these measurements had to be downloaded periodically from the buses for off-line analysis. PATH designed and performed the data downloading procedure, developed software to pre-process the data, and provided the aggregated data to NBRTI for analysis.

Subjective Data Collection

The subjective data were collected by NBRTI via subject surveys and interviews of bus operators and a rider focus group. The surveys and interviews of bus operators needed to be conducted with particular sensitivity to unions and management/labor relations. LTD organized the rider focus group.

Analysis of System Performance Data

The performance of the VAA system was assessed using a number of metrics, which are discussed in the subsequent sections.

Tracking Accuracy

Tracking accuracy was analyzed in terms of the lateral offset of the bus from the local lane center at the front magnetometer location. The lateral offset was measured more frequently (e.g., greater than 10 Hz) to facilitate smooth control performance, but it was recorded less frequently to economize on data storage. Since the LTD bus ran along the same route, data from multiple runs could be aligned by distance along the route, and composite measures of tracking accuracy as a function of location could be computed, including mean, standard deviation, and maximum offsets versus distance along the route. Precision docking accuracy was treated as a special case of tracking accuracy; it was the tracking accuracy at the locations of the EmX stations. Therefore, the data corresponding to the docking maneuvers could be identified based on the station location, and these portions of the data could be analyzed to provide statistics for docking accuracy, including mean, standard deviation, and maximum lateral offset for each docking station as well as those for all docking stations.

Ride Quality/Smoothness

The smoothness of lateral ride was measured by lateral acceleration, both slowly-varying accelerations associated with following curved road profiles and more rapid variations associated with steering corrections against disturbances. An assessment could be made by comparing the lateral accelerations under driver manual control with the lateral accelerations under VAA steering assist. The aggressiveness of curving behavior was indicated by the peak lateral accelerations as a function of location along the route.

System Robustness

Robustness describes the ability of the system to maintain consistent performance under a variety of operating conditions. In this regard, the standard deviation of tracking errors is a first rough indicator of robustness. To understand the factors that may limit system robustness, it is necessary to associate tracking errors with independent measurements that could indicate the presence of disturbances. Examples of these are local wind speed and direction (imposing lateral forces), rain or wet pavement (changing tire/road coefficient of friction), bus speed, and current passenger loading (changes of vehicle mass). To isolate the effects of these variables on system performance, the independent measurements should be used as sorting criteria to group tracking error data so they can be compared. For example, times during the operational tests when crosswind speed exceeded 25 mph should be identified and tracking error data for the buses driving at these times should be analyzed and compared with data for times when this threshold value was not exceeded. Similar analyses should be conducted to compare wet and dry pavement conditions, driving at slower and faster speeds, and lightly- and heavily-loaded bus conditions to determine the extent to which these conditions affect the VAA system performance. However, if the aggregated data over an extensive period of operations show little variation in the standard deviations across the board, there may be no need to perform the above analysis.

System Availability

Availability is a measure of the percentage of the time that the system is able to operate compared to the time when it is expected to operate. This can be established from experimental data by computing its inverse, identifying the amount of time the VAA guidance system was in a fault mode (inoperative or degraded operation) and dividing it by the total time when the VAA guidance system was expected to operate.

Safety-Related Observations

Safety concerns should be identified both quantitatively and qualitatively and compared with each other for verification. Quantitative measurements that could reveal potential safety problems include:

- Braking by the driver exceeding a threshold value of 0.3 g
- Steering maneuver by the driver exceeding a steering wheel rotation rate of x degrees per second
- Automatic steering action exceeding a steering wheel rotation rate
- Lateral position error exceeding 25 cm when under automatic steering control
- Driver intervention to override automatic steering control
- Fault indication by VAA system, transferring control back to driver

By sorting through the recorded data, these quantitative measures can be identified and flagged. Qualitative measures are safety concerns indicated by driver log reports of failures, crashes, or performance anomalies.

Quantitative measures do not necessarily mean that there has been a safety problem, but they indicate conditions that should be investigated by an analyst to determine if safety problems occurred, particularly when more than one of the measures occurs at about the same time. They need to be matched with the qualitative measures based on driver log reports of failures, crashes, or performance anomalies.

Fault Management Events

The instances in which the VAA fault management system was invoked were recorded. The precursors to these fault management actions needed to be analyzed so that the causes of the faults could be identified. These instances were expected to be rare, and if they occurred, they were to be explored individually by a skilled analyst studying the full range of recorded data available.

Driver Responses to Events

Each driver intervention to override the VAA system was investigated during the early stages of the operational tests to determine which interventions were benign (normal driving decisions), which were caused by uncontrollable external events (cut-in vehicles), and which were associated with adverse behavior of the VAA system, so attention could be focused on the latter. Based on investigation of these early override events, sorting criteria were defined to enable automatic sorting of large volumes of later operational test data to focus on the overrides associated with adverse VAA behavior. The analysis of these overrides focused on their frequency of occurrence and explanatory variables that indicated enhanced likelihood of overrides (specific route locations, drivers, VAA performance features, environmental or operating conditions, or VAA system faults).

Evaluation Test Plan

The purpose of the evaluation was to determine the impacts of VAA technology on various components of transit service. It also included information on lessons learned. NBRTI was responsible for planning and conducting the evaluation. The evaluation plan was developed by NBRTI with input from the transit agencies, USDOT, and the Caltrans team. The evaluation analysis areas included the following:

- Customer Satisfaction
- Bus Operator Satisfaction
- Efficiency/Productivity
- Maintenance
- Safety
- Technology Performance
- Lessons Learned

The general approach for evaluating the impacts of the VAA systems was a "with" vs. "without" comparison—a comparison of the impacts and performance of conditions with the VAA system enabled or disabled. Specific instruments, procedures, and methodologies were coordinated with the Caltrans team. PATH was responsible for VAA system quantitative data collection and processing in coordination with NBRTI. LTD provided management of customer and personnel evaluation activities with support from NBRTI and PATH. NBRTI obtained lessons learned information from interviews with key management and staff at LTD, AC Transit, Caltrans, and PATH.

Operational Test Results: Tests at LTD without Passengers

Upon the successful completion of system testing, operational testing without passengers was conducted for the LTD lane-keeping and precision docking operations in Eugene. The operational tests were not conducted for the AC Transit VAA applications. This section presents the results for the first part of the operational tests at LTD for the EmX route testing without passengers. The results of the second part of the operational tests—revenue service—include the engineering and statistic results for evaluation and are reported separately.

During operational testing without passengers in May 2013, 119 round trips (6 in-bound trips) with automated steering were safely conducted along the EmX BRT route. These trips were conducted under the normal bus operational environment without PATH researchers on board. The results presented in this section are based on the data collected during these 119 round trips before commencing the revenue service testing.

Precision Docking Performance

During initial system testing before the operational testing, the researchers manually measured the horizontal gap at each of the three stations during most of the test runs. Measurements indicated that the horizontal gap was usually 3–5 cm at both the front and rear tire locations at these stations except the WB Walnut Station. Figures 5 -27, 5-28, and 5-29 show typical docking performance. To achieve the same horizontal gap at the WB Walnut Station, the VAA system required quick changes in the steering command; however, the drivers tended to feel uncomfortable with such sharp steering operations. As a compromise between control precision and driver perception, precision docking at WB Walnut Station was adjusted to achieve a 3–5 cm horizontal gap at the front tire and a 5–7 cm horizontal gap at the rear tire location.

Figure 5-27

Precision docking at Walnut Station (EB)

Figure 5-28

Precision docking at Agate Station (WB and EB)

Figure 5-29

Precision docking at Dad's Gate Station (WB and EB)

Lane-keeping Performance

Table 5-1 shows the statistics of the lane-keeping performance for the final system based on the 119 round trips with automated steering during the operational testing without passengers in May 2013. As a comparison, the statistics of the manual lane-keeping performance in April and May are also included. The final VAA system achieved lateral positions of about 7.4 cm standard deviation (STD), larger than the initial 5 cm STD but still less than half of the 16.7 cm STD that occurred during manual driving.

Table 5-1

Statistics of Lateral Position (based on all trips made in April and May, 2013)

Measure	Trips with Automated Steering			Trips with Manual Driving		
	WB Trips (n=191)	*EB Trips (n=25)*	*All Trips*	*WB Trips (n=114)*	*EB Trips (n=108)*	*All Trips*
STD (m)	0.078	0.071	0.074	0.169	0.163	0.167
Mean (m)	0.002	-0.001	0.0007	-0.036	0.002	-0.016

*STD = standard deviation

Figure 5-30 shows the lateral positions of all trips made by the VAA-equipped bus in April and May 2013. (The same data were used to generate the statistics shown in Table 5-1.) The lateral positions are plotted against their corresponding magnet marker number and were direct measurements from the front magnetometer sensor bar and updated when a magnet marker was detected. The top figure shows the lateral positions for trips with automated steering, and the bottom plot shows the lateral positions for trips with manual driving. In both plots, the positions in blue without red or green dots correspond to the lateral positions on docking curves. Since the focus was on lane-keeping performance, these lateral positions on docking curves were excluded from the analysis. The red dots in the top plot mark the lateral positions under automated lane-keeping control, and the green dots in the bottom plot marks the lateral positions under manual lane-keeping. The number of trips with automated steering is comparable to the number of trips with manual driving.

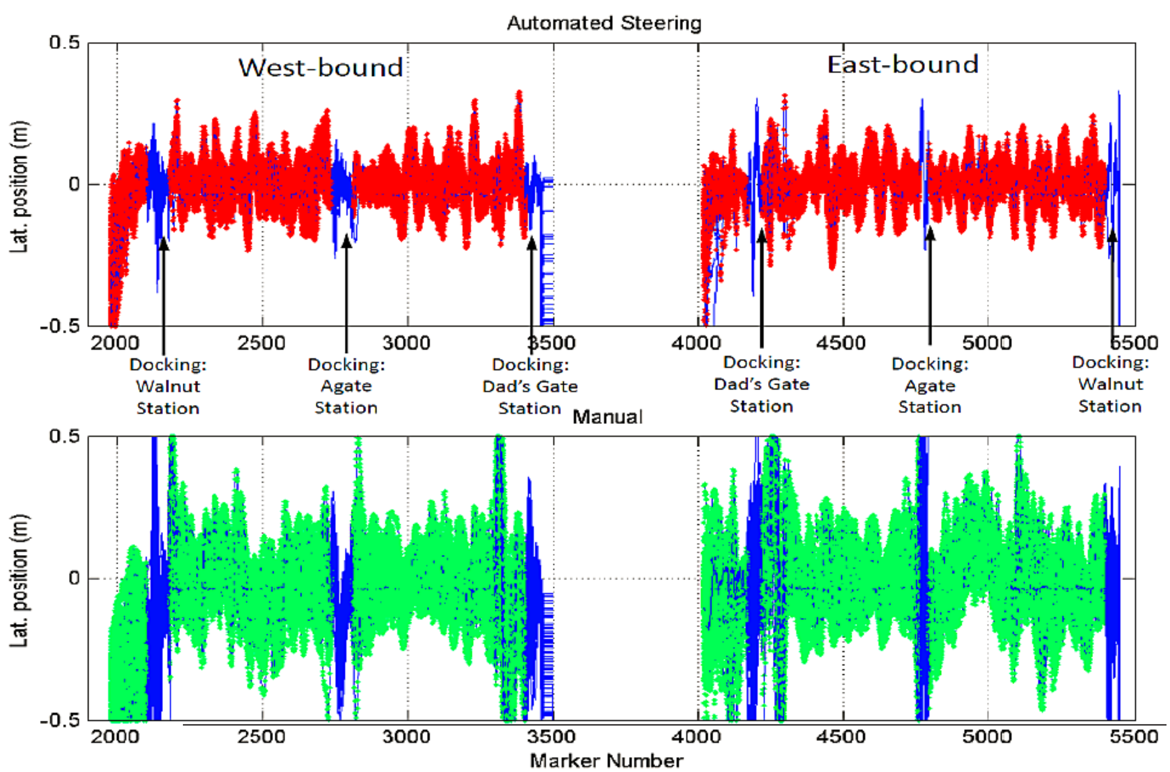

Figure 5-30

Comparison of lateral positions (automated steering vs. manual driving)

From Figure 5-30, it is clear that the VAA system achieved noticeably smaller and more consistent lateral positions than those that occurred during manual operations. The plots are also consistent with the fact that the STD of the lateral positions under automated steering is less than half of the STD of the lateral positions achieved by manual driving. These results verify that the VAA system is capable of maintaining vehicles within a lane and providing a relatively smooth ride in narrow and curvy pathways.

Operational Testing Data Examination

To help explain how the automated system was operated and performed, this section presents data of WB and EB runs during the operational testing without passengers. Those two runs were selected from the first round trip made by an operator on May 14, 2013.

Figure 5-31 shows the lateral position (relative to the magnet track) measured by the front sensor bar, vehicle speed, and status of the LED lights and the auto/manual toggle switch for the first four seconds of the selected WB run. The time “0” corresponds to the time when the bus detected the first magnet about 840 ft (256 m) before Walnut Station. As shown in Figure 5-31, the amber LED was lit at the beginning, indicating that the automatic system was not ready for transition. Within 0.5 seconds from the time the bus detected the first magnet, the green LED was lit, indicating that the automatic system was ready for transition. A beep was issued at the time the green LED was lit to inform the driver that the system was ready for transition. The driver switched to “auto” at about 0.5 second after the beep, and the blue LED was immediately lit, showing that the system had transitioned to the automation mode. Two beeps (recorded as one long beep) were issued at the same time to notify the driver of the transition; upon hearing the beeps, the driver then released the ON/OFF toggle switch. The amber LED remained lit until a code (i.e., a milepost) was read from the magnet track at about 2.2 seconds (the codes serve as mileposts to let the bus know where it is at along the EmX track). The bus was then guided to approach Walnut Station.

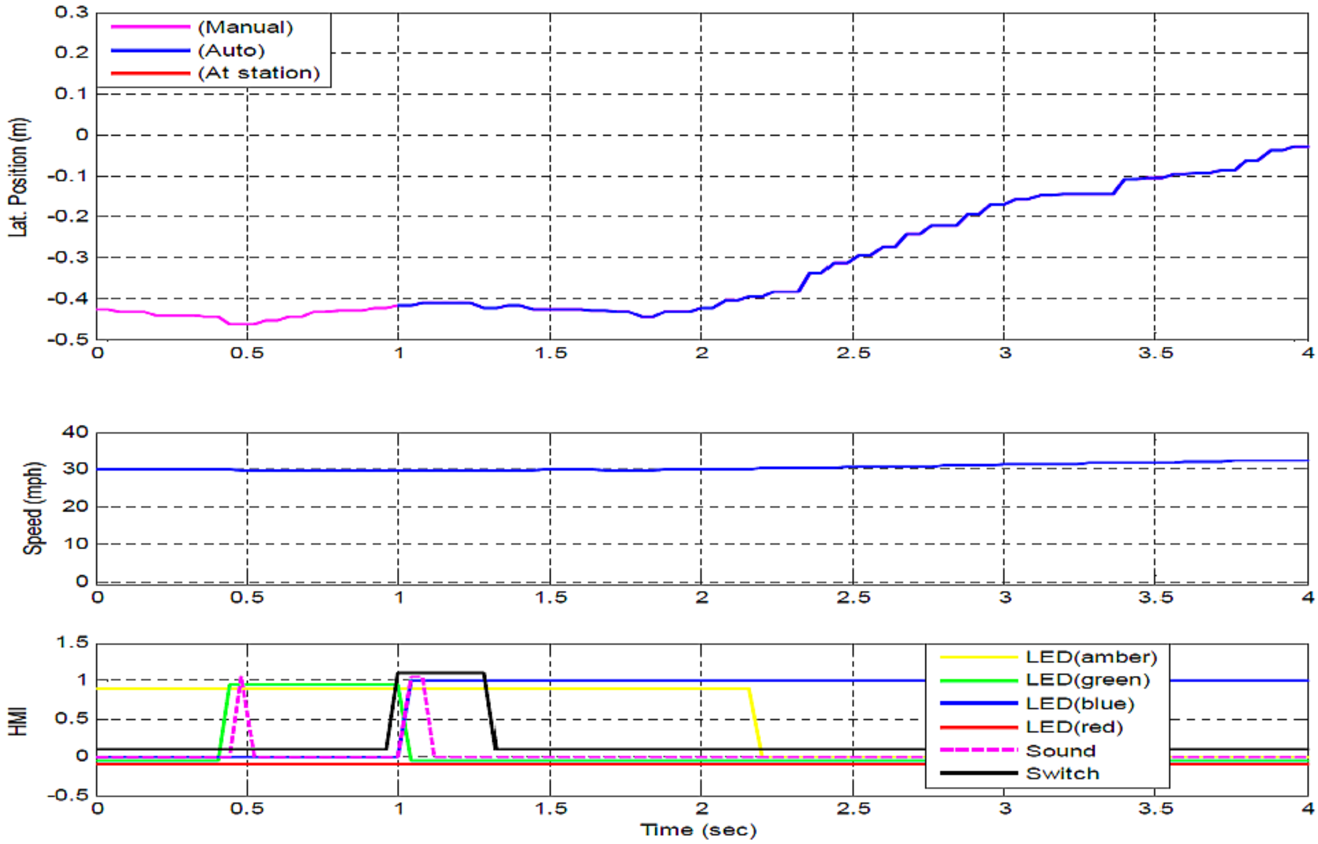

Figure 5-31

EmX WB run—lateral position error, speed, and HMI LEDs & switch

Figure 5-32 shows the complete time traces of the same signals (lateral position, vehicle speed, LED lights, switch) shown in Figure 5-31. At around 7–9 seconds, the bus speed exceeded 35mph, and the amber LED blinked to provide a speed warning to the driver. At around 30 seconds, the bus arrived at Walnut Station; the amber LED blinked, informing the driver of the final stop location. The bus stopped at Walnut Station for about 103 seconds before leaving the station under automated steering control. The bus then came to a stop for the traffic light at Villard Street for 18 seconds and continued following the magnets through a large S-curve (two curves of radius 97.5 m) before it reached Agate Station at 255 seconds. Similarly, the amber LED blinked, notifying the driver of the final stop location at the station. After a 43-second stop at Agate Station, the bus continued traveling through Onyx Street. During that time, the amber LED blinked again to remind the driver of the excess speed at around 322 seconds. After stopping for the traffic light at E 11 Avenue, the bus made a sharp left turn onto E 11 Avenue and arrived at Dad's Gate Station, the last station on the magnet track, at around 370 seconds. The amber LED blinked again as the bus reached the final stop location at Dad's Gate Station. After stopping at the station for 11 seconds, the driver overrode the automatic system by taking over the steering wheel before he/she drove the bus away from the station. The blue LED was turned off, and the amber LED was lit to indicate that the automatic system was disengaged and not ready for transition. A beep was also issued at the same time to indicate the transition.

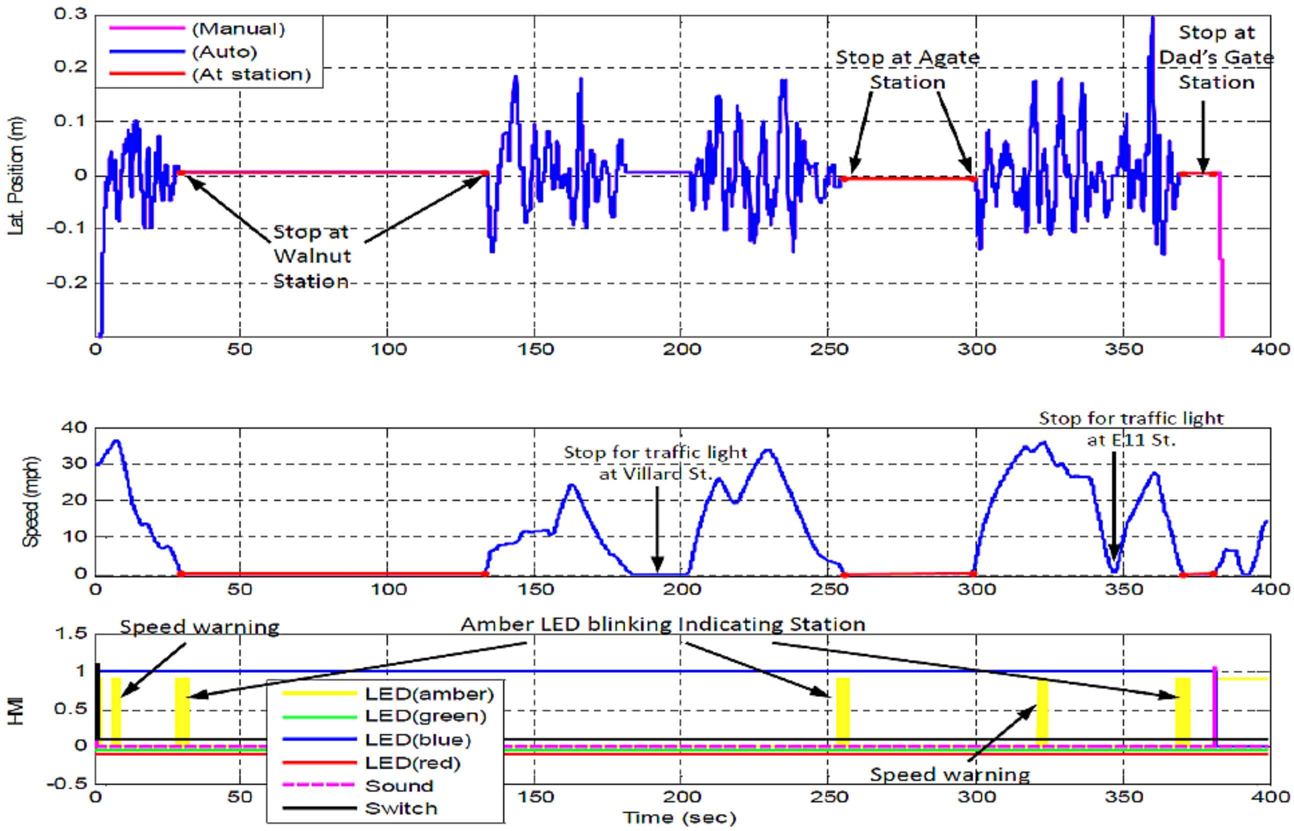

Figure 5-32

EmX WB run—lateral position error, speed, and HMI LEDs & switch

For this WB run, the bus was under automatic control almost the entire run. Except for the sharp left turn onto E 11 Avenue, the lateral positions (with respect the magnet track) never exceeded 20 cm. The lateral positions[15] at each station were 6 mm at Walnut Station, -6 mm at Agate Station, and 3 mm at Dad's Gate Station. Given that the target horizontal gap at the station platform was 4 cm, the actual horizontal gaps at the stations were 4.6 cm at Walnut Station, 3.4 cm at Agate Station, and 4.3 cm at Dad's Gate Station.

Two observations regarding the lateral position are worth mentioning. First, the sharp turn from Franklin Boulevard to E 11 Avenue (or from E 11 Avenue to Franklin Boulevard for the EB run) has a minimum radius of 46.6 m. Drivers

[15]A position (or negative) lateral position indicates that the bus is to the left (or right) of the desired position (defined by the magnet track). Since the platforms of the three stations are to the left of the bus, a position (or negative) lateral position at the station indicates that the bus is closer to (or farther away from) the platform than the desired position.

typically cut corners when maneuvering the 60-ft bus through the turn; the bus often deviates from the magnet track for as much as 1 m in both directions depending on the travel direction. However, for the magnet-guidance system, only one magnet track is installed for both travel directions, and the sensing range of the magnetometer sensor bars makes it infeasible to guide the bus through the turn with a large offset or deviation. As a result, the bus went through the sharper turn with a close to 30 cm deviation (by increasing the front tracking error that the offset tracking at the rear end of the bus can be reduced).

Second, the VAA system initially was designed to follow the magnet track with higher precision. However, drivers and passengers who stood close to the front of the bus experienced a jerky ride. The tight control required the steering control to make corrections constantly to exactly follow the relatively sharp curves along the EmX Route. Therefore, the VAA system was re-tuned to achieve a balance between lane-keeping accuracy and ride comfort. Figure 5-32 shows the performance of the final VAA system, where the lateral deviations were within 20 cm (except on the sharp turn onto E 11 Avenue to reduce the offset tracking on rear end of the bus.).

Figure 5-33 shows the lateral positions and vehicle speed with respect to the travel distance from the first magnet (i.e., the location on the magnet track). Plotting variables with respect to the travel distance from the first magnet provides insights in the relationship between the control performance and the road geometry; it facilitates direct comparison among multiple runs and an analysis of the control consistency.

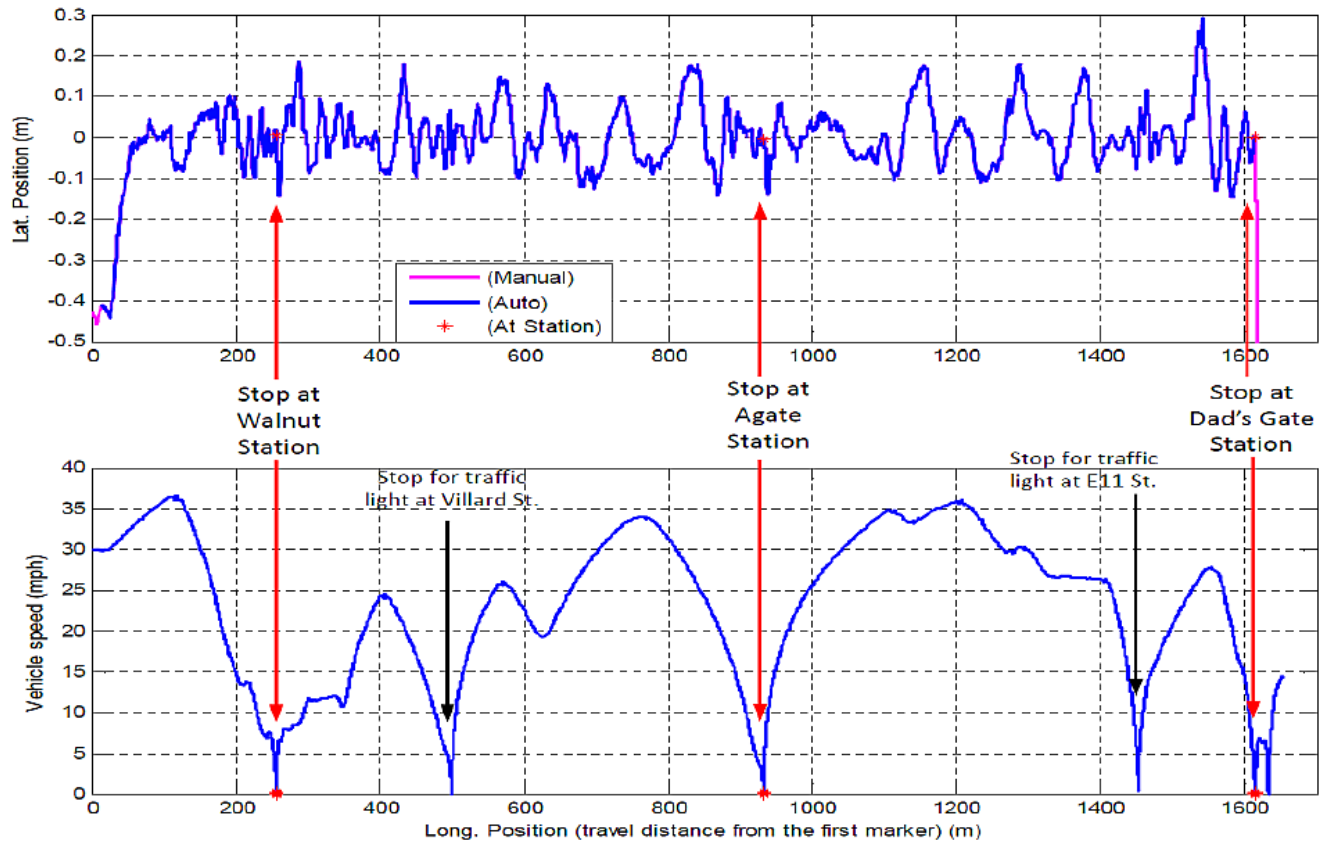

Figure 5-33

EmX WB run—lateral position error and speed (distance-based)(time-based)

Figure 5-34 shows the lateral positions and vehicle heading angle with respect to the travel distance from the first magnet. The vehicle heading angle (with respect to the magnet track) was computed based on the lateral positions measured by the front and rear magnetometer sensor bars. As shown in Figure 5-34, the vehicle angle was within 3 deg except at the docking curve into Walnut Station (at around 211 m), the curve out of Walnut Station (at around 280 m), and the sharp turn onto E 11 Avenue (at around 1470 m). Moreover, the vehicle angle quickly converged to smaller than 0.1 deg once the bus completed the docking curve and stopped at the stations, indicating the bus was almost parallel to the platform.

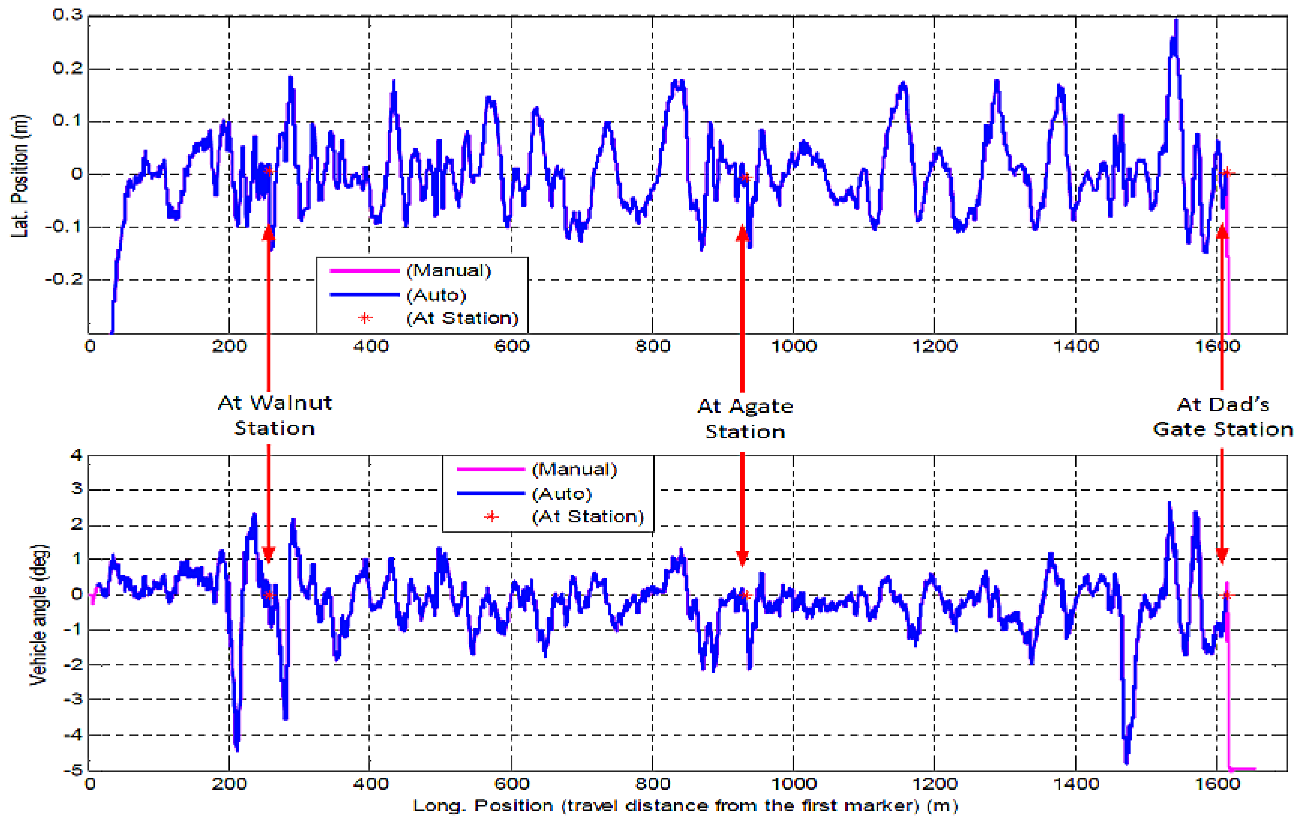

Figure 5-34

EmX WB run—lateral position error and vehicle angle (distance-based)

Figure 5-35 plots the steering angle and the steering angle command of the steering wheel with respect to the travel distance. The steering command, together with the lateral positions (Figure 5-33) and vehicle angle (Figure 5-34), at the transition between manual driving and automatic control indicates smooth transitions. The steering angle on the EmX route, in general, was less than 100 deg in either rotation direction. The steering angle reached its maximum of 213 deg during the sharp turn from Franklin Boulevard to E 11 Avenue. Large steering angles also occurred at the curves into and out of Walnut Station, the sharp S-curve (two curves with radius of 97.5 m) leading to Agate Station, and the docking curve to Dad's Gate Station.

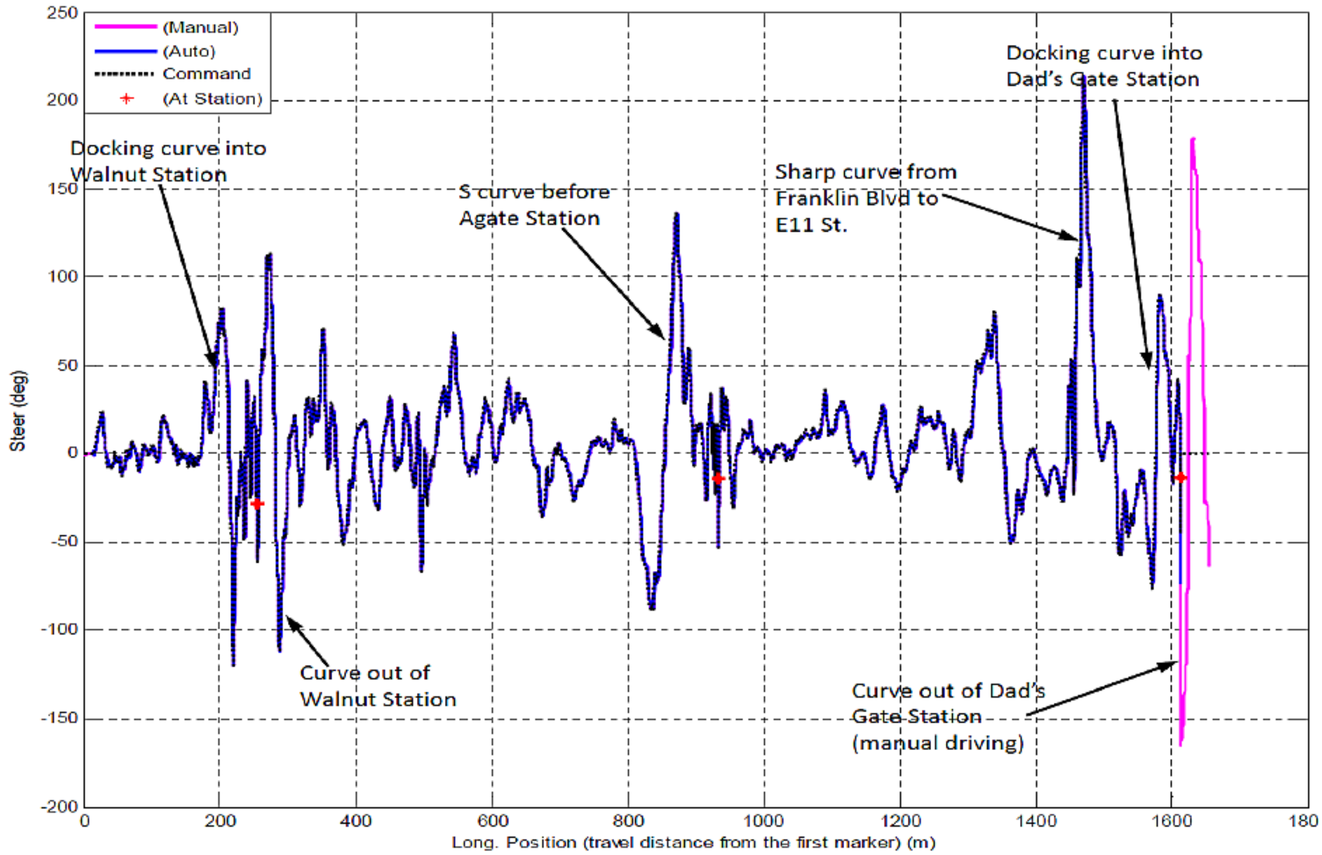

Figure 5-35

EmX WB run—steering angle and command of the steering wheel (distance-based)

Similar to Figure 5-32, Figure 5-36 shows the time traces of the lateral position, vehicle speed, LED lights, and switch for the selected EB run. Similar to the WB run, the VAA system became transition-ready at about 0.4 seconds after the first magnet was detected. The driver switched to automation mode at about 1.5 seconds after the system was ready for transition, and the blue LED was immediately lit, showing that the system had transitioned to the automation mode. The bus was then guided to follow the magnet track and arrived at Dad's Gate Station at around 101 seconds. In this run, the bus actually stopped before the desired stop location and then crept forward to finally stop at the desired stop location.[16] The amber LED blinked as the bus reached the desired stop location.

[16]The desired stop location at each station was determined such that the bus doors were aligned with the marked boarding area at the platform.

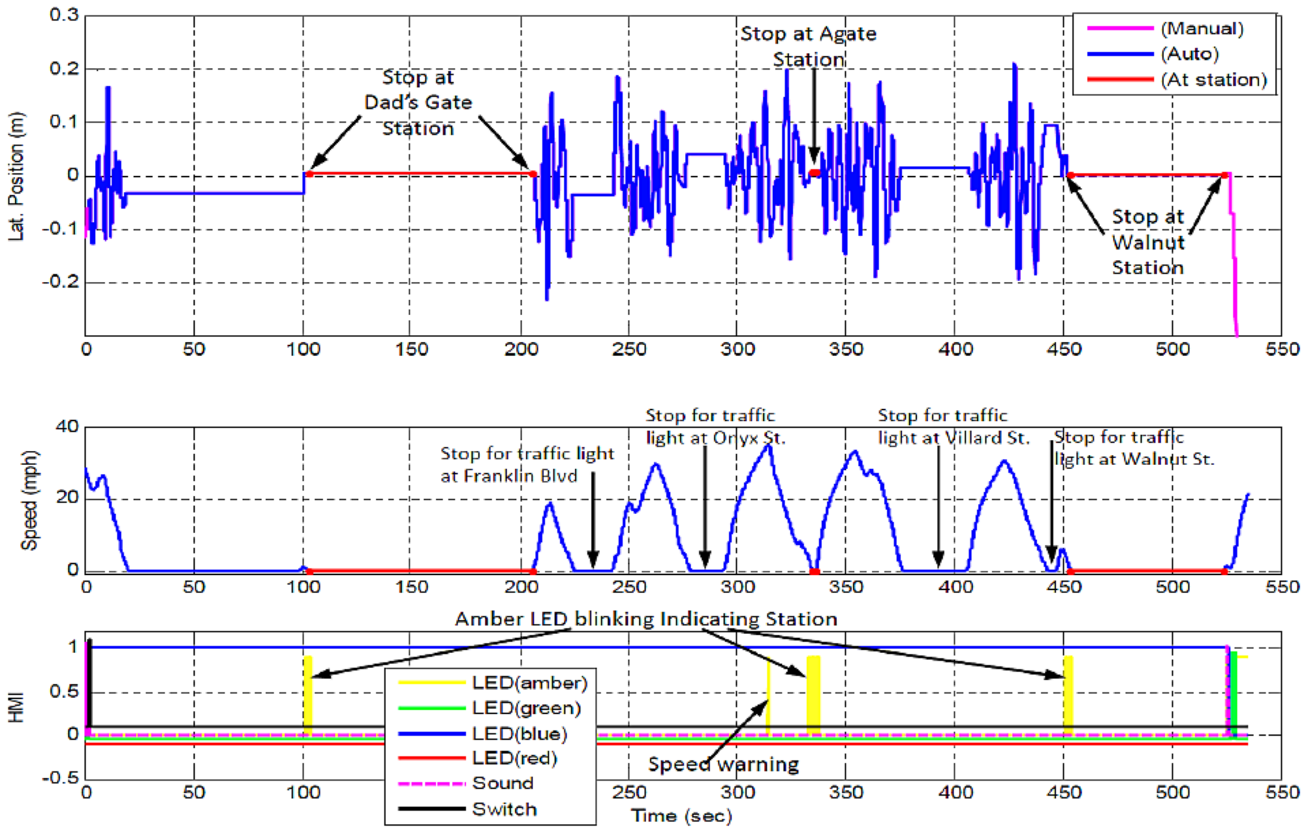

Figure 5-36

EmX EB run—lateral position error, speed, and HMI LEDs & switch (time-based)

After stopping at Dad's Gate Station for about 102 seconds, the bus left the station under automatic steering control and stopped for the traffic light at Franklin Boulevard at around 225 seconds. After a 17-second stop, the bus made the sharp right turn onto Franklin Boulevard and came to a stop again for the traffic light at Onyx Street. At 293 seconds, the bus went through the Onyx Street intersection and arrived at Agate Station at 334 seconds. At 314 seconds, the amber LED blinked for a speed warning as the vehicle speed reached 35 mph on a curve. After a brief 1-second stop at Agate Station, the bus continued, stopped for traffic lights at Villard Street and Walnut Street and then arrived at Walnut Station at 453 seconds. The amber LED blinked, notifying the driver of the final stop location at the station. After stopping at Walnut Station for 71 seconds, the driver overrode the automatic system by taking over the steering wheel before he/she steered the bus away from Walnut Station. The blue LED turned off immediately, and the green LED lit (since the bus was on the magnet track), indicating that the automatic system was disengaged but the system could still transition to automatic control. A beep was also issued at the same time to indicate the transition. As the bus drove away from the magnet track, the green LED turned off and the amber LED lit, indicating that the automatic system was not ready for transition.

For this EB run, the bus was under automatic control the entire run. The lateral positions (with respect the magnet track) almost never exceeded 20 cm. The lateral positions at each station were 6 mm[17] at Dad's Gate Station, 7 mm at Agate Station, and 2 mm at Walnut Station. Given that the target horizontal gap at the station platform was 4 cm, the actual horizontal gaps at the stations were 4.6 cm at Walnut Station, 4.7 cm at Agate Station, and 4.2 cm at Dad's Gate Station.

Figures 5-37 and 5-38 show the lateral position, vehicle speed, and vehicle heading angle with respect to the distance traveled from the first magnet for the EB run. As shown in Figure 5-38, the vehicle angle was within 2 deg except at the docking curve into Dad's Gate Station, the curve out of Dad's Gate Station, the sharp right turn from E 11 Avenue to Franklin Boulevard, the docking curve into Agate Station, and the docking curve into Walnut Station. Similar to the WB run, the vehicle angle quickly converged to be smaller than 0.1 deg once the bus completed the docking curve and stopped at the stations, indicating the bus was almost parallel to the platform.

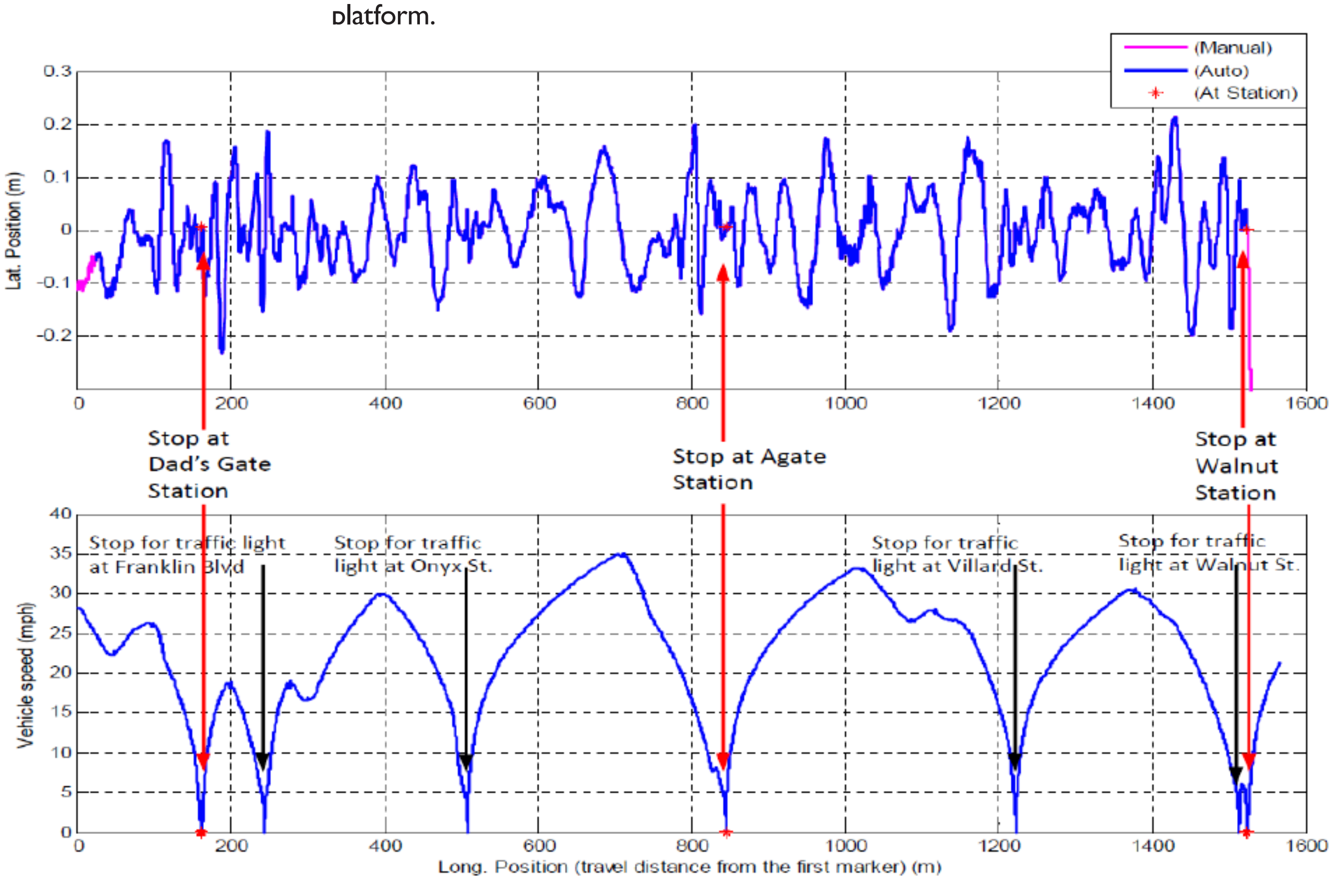

Figure 5-37

EmX EB run—lateral position error and speed (distance-based)

[17]A position (or negative) lateral position indicates that the bus is to the left (or right) of the magnet track. Since the platforms of the three stations are to the left of the bus, a position (or negative) lateral position at the station indicates that the bus is closer to (or farther away from) the platform than the desired position.

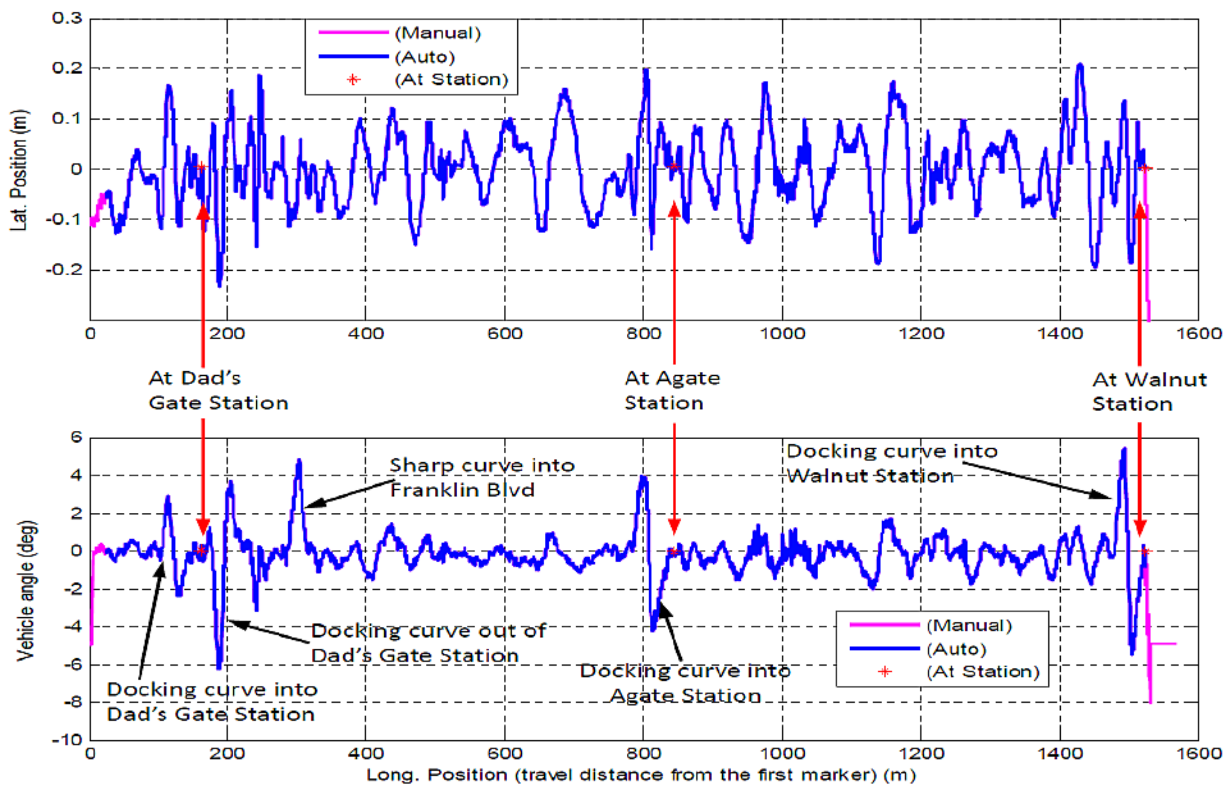

Figure 5-38

EmX EB run—lateral position error and vehicle angle (distance-based)

Figure 5-39 plots the steering angle and the steering angle command of the steering wheel with respect to the travel distance. The steering command, together with the lateral positions (Figure 5-37) and vehicle angle (Figure 5-38), at the transition between manual driving and automatic control indicates smooth transitions. The steering angle on the EmX route was in general less than 100 deg. The steering angle reached its maximum of 215 deg on the docking curve into Agate Station (where the bus made more than 2 lane changes within 223 ft). Large steering angles over 150 deg also were observed on the sharp right turn from E 11 Avenue to Franklin Boulevard and the docking curve into Walnut Station. These larger steering angles were the result of tightly following the magnet track.

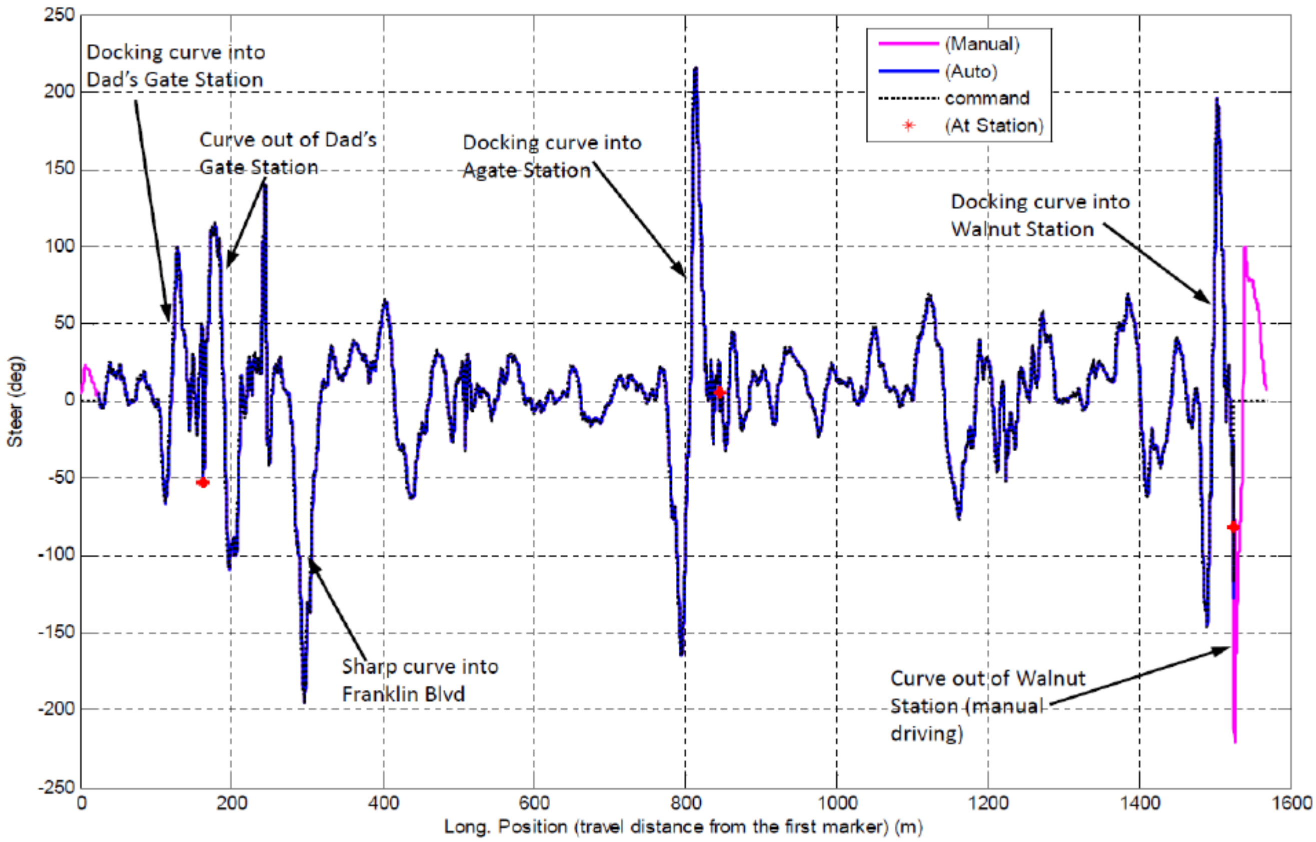

Figure 5-39

EmX EB run—steering angle and command of steering wheel (distance-based)

Operational Tests: Revenue Service Results

Upon successful completion of the field testing without passengers, VAA operations in revenue service started on June 10, 2013; however, after operating for almost five months, VAA operations in revenue service were suspended on October 15, 2013, due to contractual issues. After the contractual issues were resolved in September 2014, VAA operations in revenue service resumed on October 11, 2014. A total of more than 28 operators were trained and had used the automated bus in revenue service. Until the end of October 2013, a total of 975 round trips were made by the equipped bus. Among them, 448 round trips were under automatic steering (i.e., VAA-enabled); the remainder of the trips were in manual mode.

For operational testing with passengers, the goals of data collection included measuring operational improvements due to the introduction of VAA, identifying VAA faults encountered in real-world transit operations, understanding driver and passenger perceptions during the revenue service of the VAA system, and assessing the impact of the VAA technologies on maintenance.

Vehicle Position

The revenue-service data showed that the final system achieved lateral positions of about 7.1 cm STD (including the S-curve docking), which satisfies the requirements and is less than half of the STD (16.7 cm) achieved by manual driving. Figure 5-40 shows the position error, speed, and steering wheel angle of one WB revenue service run with respect to the travel distance from the beginning of the magnet track. The steering angle reached its maximum of 213 deg during the sharp turn (35 m radius) from Franklin Boulevard to E 11 Avenue. Large steering angles also occurred at the curves into and out of Walnut Station, the sharp S-curve leading to Agate Station, and the docking curve to Dad's Gate Station. On the other hand, the lateral error never exceeded 20 cm except on the sharp docking curve leading to Dad's Gate Station.

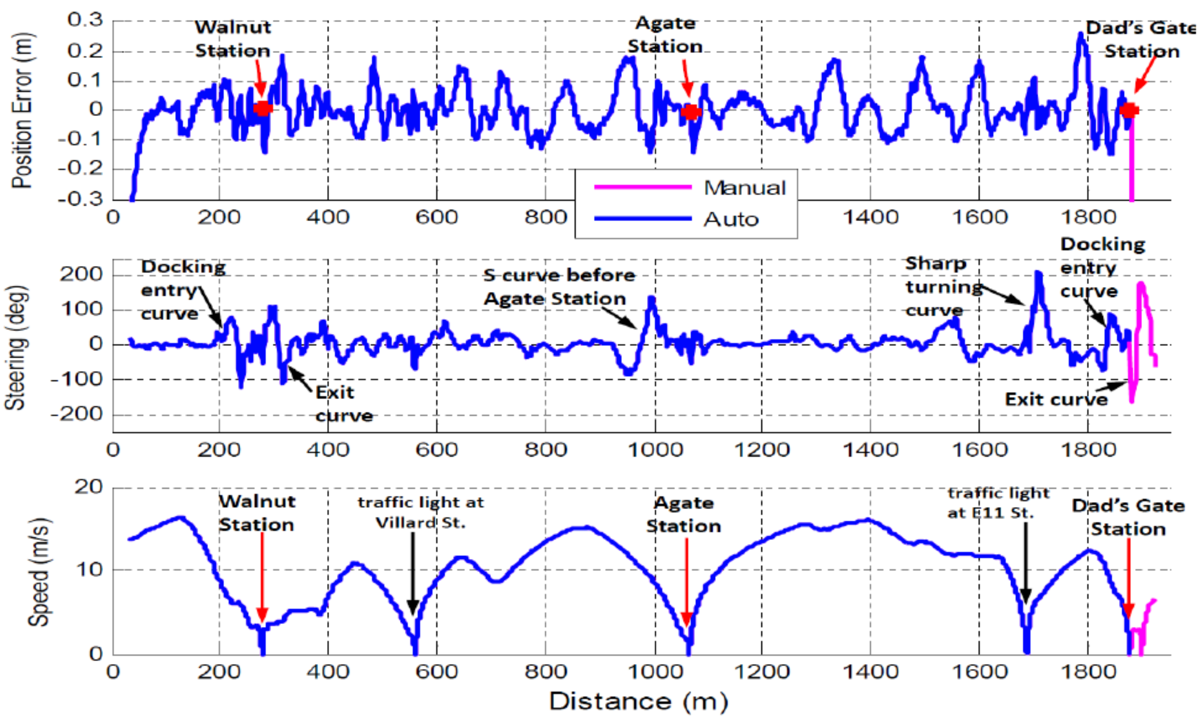

Figure 5-40

EmX WB revenue service run—lateral position error, steering wheel angle, and speed (distance-based)

Figure 5-41 shows the position error, speed, and steering wheel angle of one EB revenue service run. Except on docking curves, the lateral error never exceeded 20 cm. The horizontal gaps at the stations were 4.6 cm at Walnut Station, 4.7 cm at Agate Station, and 4.2 cm at Dad's Gate Station.

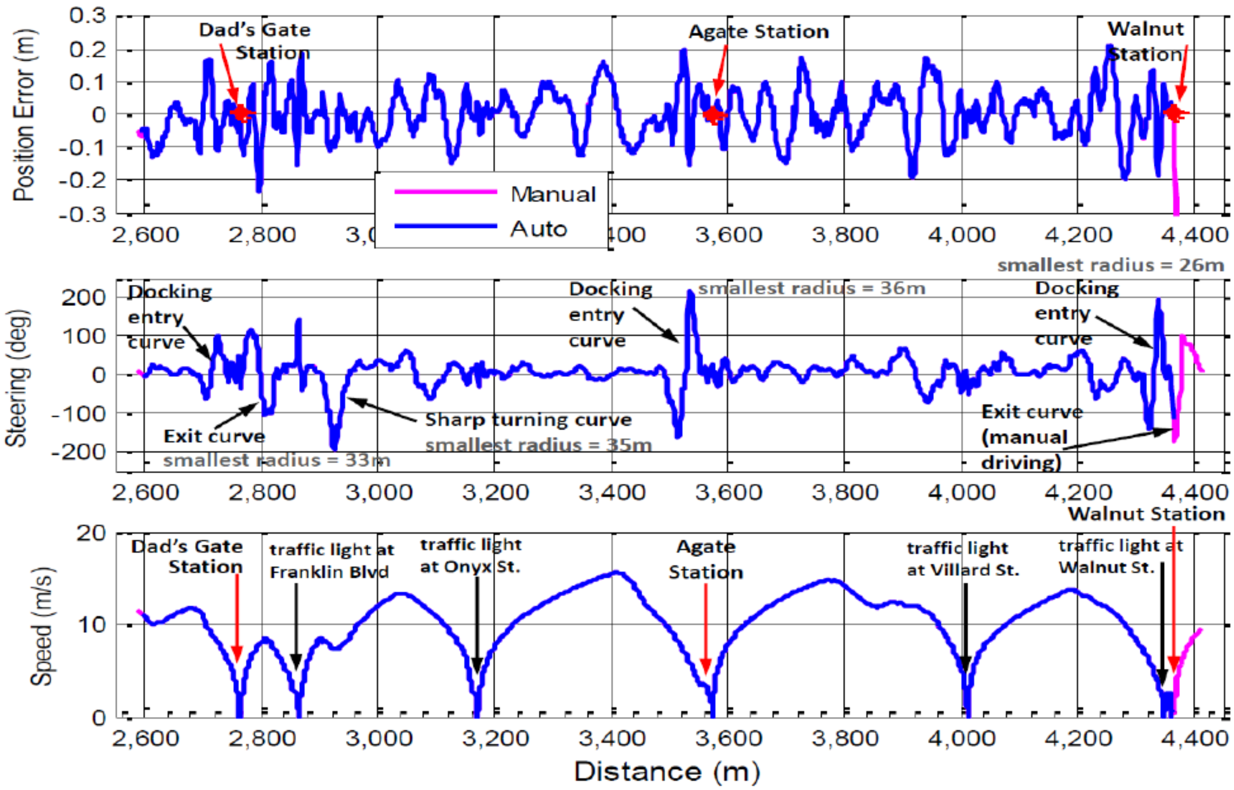

Figure 5-41

EmX EB revenue service run—lateral position error, steering wheel angle, and speed (distance-based)

Figure 5-42 shows the data for WB runs during revenue service in July 2013. Other than two locations (at 650 m and 1600 m) and on docking curves, the lateral position error was within 20 cm. The two locations are part of continuous curves at which the front part of the bus was deliberately offset to avoid the rear articulated section touching the curb, and the amount of offset depended on vehicle speed.

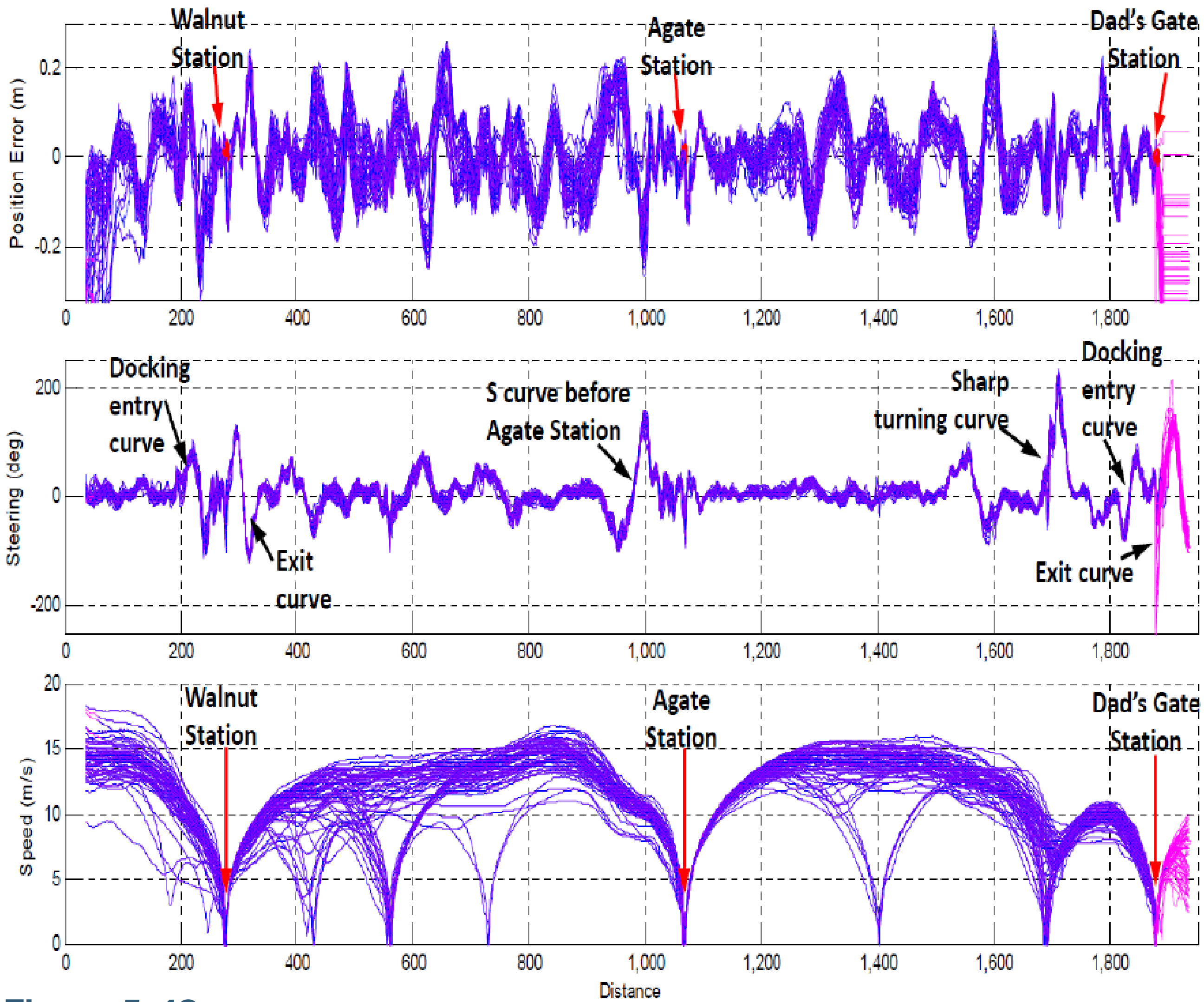

Figure 5-42

EmX WB revenue service runs in July 2013—lateral position error, steering wheel angle, and vehicle speed (distance-based)

Precision docking was performed at six locations (three stations in each direction). The target horizontal gap for precision docking was 4 cm between the vehicle and platform edge. Measurements at stations indicated that the horizontal gap was usually 3–5 cm at both the front and rear tire locations at all three stations. Data from revenue service confirmed that the position errors were almost all within 2.5 cm (i.e., STD about 0.8 cm) of the nominal 4 cm. More specifically, the STDs at the six locations were 1.01 cm, 0.77 cm, 0.85 cm, 0.79 cm, 0.45 cm, and 0.93 cm, respectively.

Figure 5-43 shows the docking performance at the two most challenging stations—EB Agate Station and EB Walnut Station—for one day during revenue service operations. The top subplot shows the position error measured by the front (blue lines) and rear (red lines) sensor bars. The speed shown in the bottom subplot illustrates the variation in driver speeds. Drivers entered the docking curve at speeds as high as 40 km/h and reached the platform at 24 km/h (bottom left subplot). The control system performed steering corrections to pull the bus straight at the platform (both position errors go to 0). In addition, as the bus was pulling straight at the station, the steering angle exhibited larger variations (circled areas), demonstrating the effects of the controller's ability to avoid hitting the platform while achieving the consistently tight docking gap. It is worthwhile noting that the bus/tires never touched the platform/strip or curb during the entire revenue service.

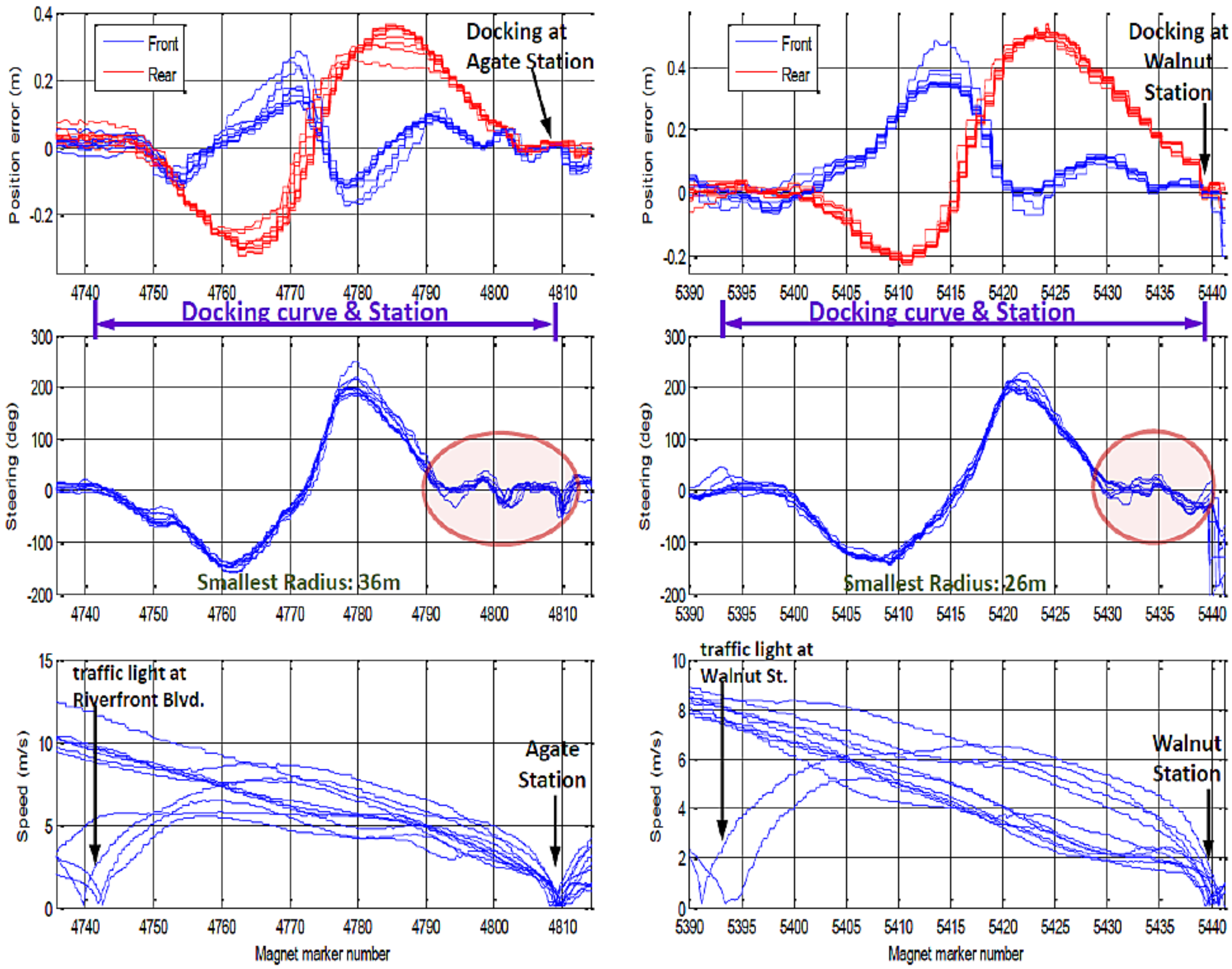

Figure 5-43

Docking performance at EB Agate Station (left) and EB Walnut Station (right) (one day of revenue service data)

One comment regarding the lane-keeping performance is worth mentioning. Although the initial automated control system achieved smaller lateral deviations (5 cm STD), some operators felt the rides were jerky as the bus was tightly following the track. The reason was that the tight lane-keeping control forced the bus to "fit" the curvy track. To achieve a balance between lane-keeping accuracy and ride comfort on such a curvy route, the system gain was reduced to tolerate larger lateral deviations as long as the resultant error was under the required lateral standard deviation target (7.6 cm).

Performance Comparison: Automated Steering vs. Manual Steering

The revenue service confirmed that the automated steering achieved significantly smaller lateral errors than the manual steering. Figure 5-44 shows the lateral errors under automatic control (upper plot) and those under manual driving (bottom plot) with respect to the magnet number along the corridor. The lateral errors under automatic steering were noticeably smaller and more consistent than those under manual steering.[18] The STD for automatic steering was 7.15 cm, and the STD for manual steering was 16.81 cm. In addition, manual and automated driving generated the same level of the lateral accelerations.

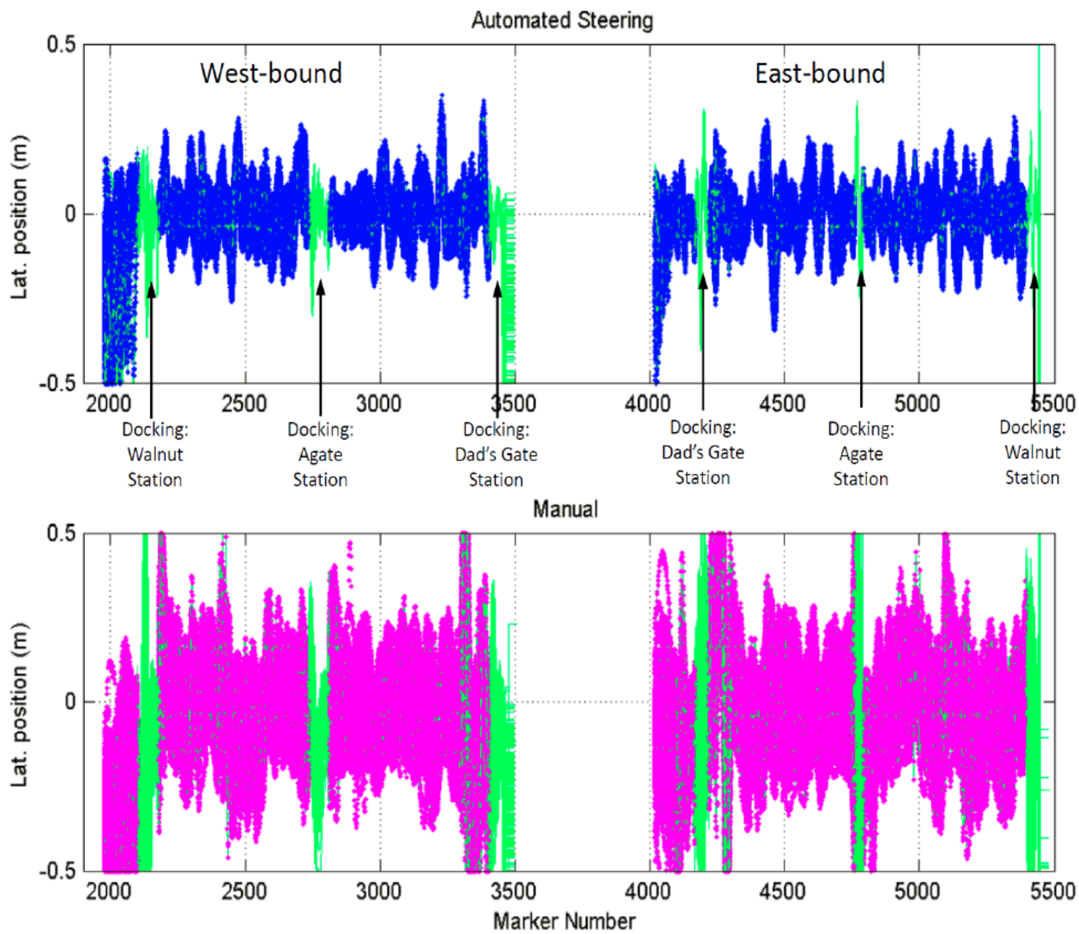

Figure 5-44

Comparison of lateral positions—automated (top) vs. manual driving (bottom)

Figure 5-45 shows the speed and steering wheel angle under revenue service operations. The blue lines and the magenta lines correspond to automatic steering control and manual steering, respectively. In general, the vehicle speeds

[18]The large errors at the beginning of the track in the top plot are due to the initial position errors that resulted from manual driving before activation.

under automation were compatible with those under manual driving, with manual steering achieving maximum speeds slightly higher (~1–1.5 m/s) than automated steering. The steering wheel angles in the bottom plot of Figure 5-45 show that the steering angles under automation were compatible with those under manual driving. Moreover, the steering angles under automation were more consistent than those under manual driving, especially on sharp curves, including docking curves. In addition, the steering angles exceeded 100 deg at more than 20 locations under either manual or automatic steering; the maximum steering rate can reach more than 300 deg/sec depending on the vehicle speed. These observations again reflect that this narrow corridor was indeed a challenging BRT route from the perspectives of performance and safety.

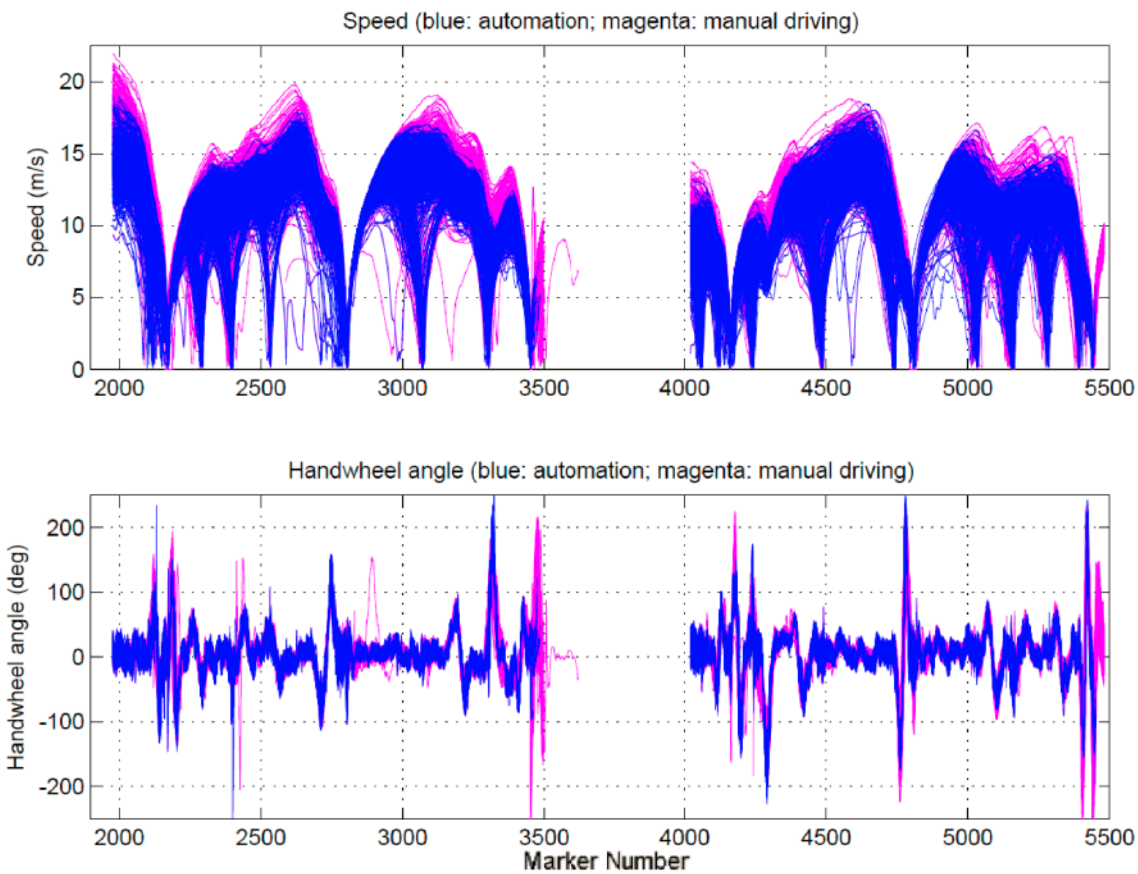

Figure 5-45

Revenue service—bus speed (top) and steering wheel angle (bottom)

Revenue Service Results: Statistics

As stated previously, measurements describing the operation of the vehicle and the VAA system were recorded by an on-board data acquisition system to support the assessment of VAA system performance. Data recorded during revenue service operations are especially helpful to evaluate the operational improvements due to the introduction of VAA through quantitative technical performance of the VAA systems in real-world conditions and to identify VAA faults that could be encountered in real-world transit operations, including their frequency of occurrence. In this section, the statistical results based on data recorded during revenue service are presented.

After every new driver bid process, some drivers who had not been trained for the VAA-equipped bus were assigned to the VAA bus operational slot, so VAA driver training had to be repeated for these new drivers. During this period, the new drivers drove the VAA bus under manual mode at his/her designated time slots before being certified to engage the VAA control for revenue service. Due to the timing and the on-and-off nature of the VAA schedule, these training events occurred throughout the entire VAA testing period. Thus, the data collected during revenue service included both the data when the bus was under automated steering and when it was under manual steering. Table 5-2 shows the number of runs under automated steering and manual steering for each month during the revenue service testing periods. Note that VAA automated steering was disabled on October 15, 2013, and did not resume until Fall 2014. For administration reasons, the automated steering was rarely turned on in November and December 2014. VAA operations in revenue service started again in January 2015. However, at the time this report was written, the 2015 data had not been analyzed.

Table 5-2

Number of Runs under Automated Steering and Manual Steering

Month	Automated Steering		Manual Steering	
	WB Runs	*EB Runs*	*WB Runs*	*EB Runs*
June 2013	70	71	106	104
July 2013	90	92	118	117
August 2013	62	61	131	130
September 2013	148	143	59	64
October 2013	78	84	113	108
November 2013	0	0	220	221
December 2013	0	0	222	222
September 2014	6	6	67	69
October 2014	85	84	134	133
November 2014	2	5	218	215
December 2014	0	0	56	56

Operational Improvements

The operational improvements achieved by the VAA system were evaluated by comparing the lateral and docking positions and the lateral accelerations under automated steering with those under manual steering. The lateral and docking positions reflect tracking accuracy and system robustness for lane-keeping and precision docking performance; lateral acceleration serves as a measure for ride quality/smoothness.

Figure 5-46 shows the standard deviation of the lane-keeping lateral deviation for each month during VAA revenue service operations. In the months in which automated steering data were available, the lane-keeping lateral deviation achieved by automated steering had an STD less than half that achieved under manual steering. Also as shown in Figure 5-46, the monthly STDs of the lane-keeping lateral deviation were between 6.07 cm and 7.68 cm for automated steering, and the monthly STDs of the lane-keeping lateral deviation are 14.79–16.84 cm for manual steering. The advantage of the automated steering is evident.

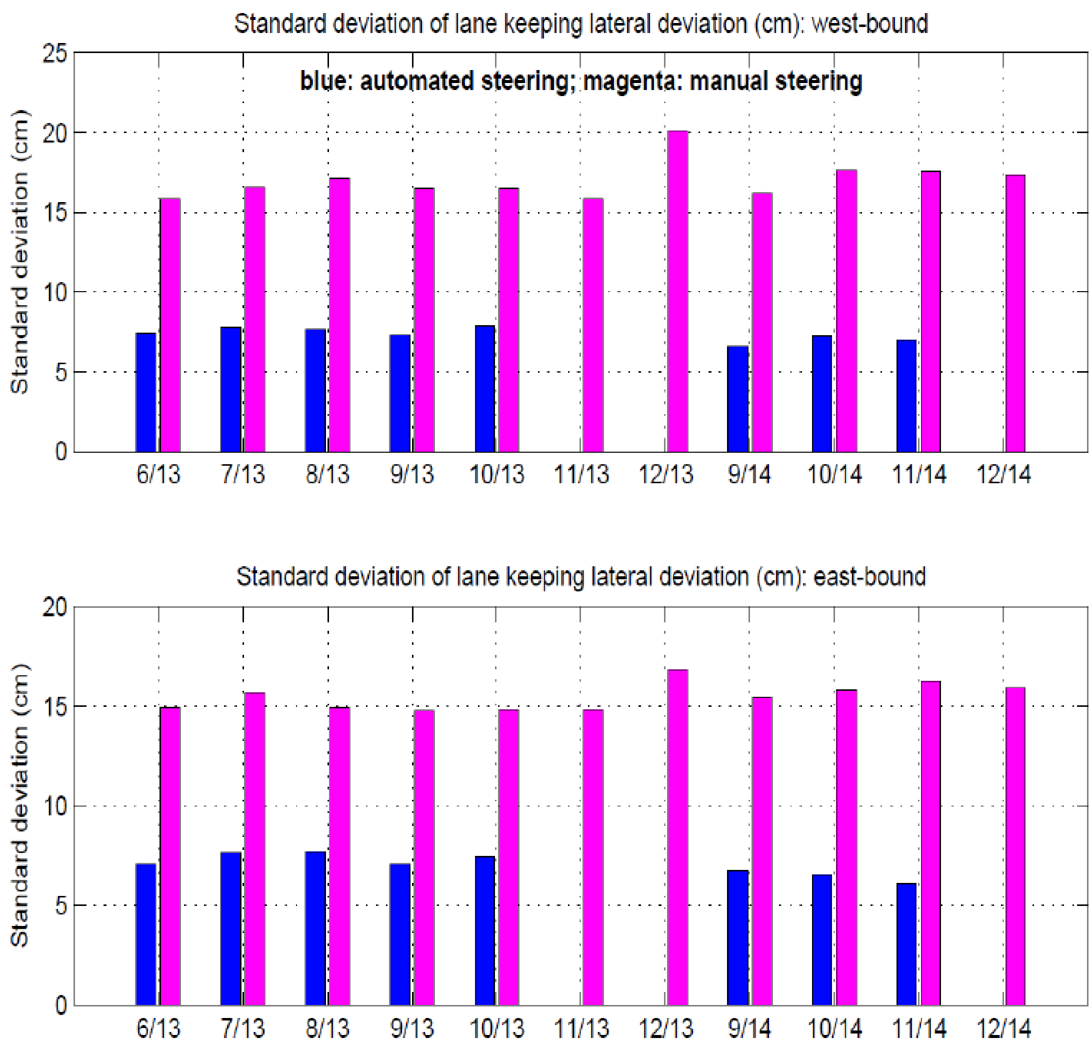

Figure 5-46

Standard deviation of lane-keeping deviation for each month of revenue service

Figure 5-47 shows the STD of the precision docking errors for each month during revenue service. The STDs of the docking errors at the six docking locations (EB and WB for each station) for manual steering (shown as magenta bars) range from 4.18 cm to 7.15 cm. The STDs of the docking errors at the same six locations under automated steering (shown as blue bars) range from 0.73 cm to 1.02 cm. If the WB Walnut Station[19] is excluded, the STDs (shown as cyan bars) under automated steering ranges from 0.71 cm to 0.85 cm, except in October and November 2014. During an investigation at the end of October 2014, it was determined that the radius rod bushings of the articulated section of the VAA bus were blown, which made the articulated section slightly warped toward the left. This issue on the articulation joint added a couple of centimeters on the tail end of the bus to the right on straight line driving. A slight increase in STD at docking during October reflects the controller's efforts to mitigate such an offset. In November 2014, for administration reasons, only two WB runs and 5 WB runs were conducted under automated steering. Thus, the precision docking data in November 2014 may not be statistically significant to represent the docking performance.

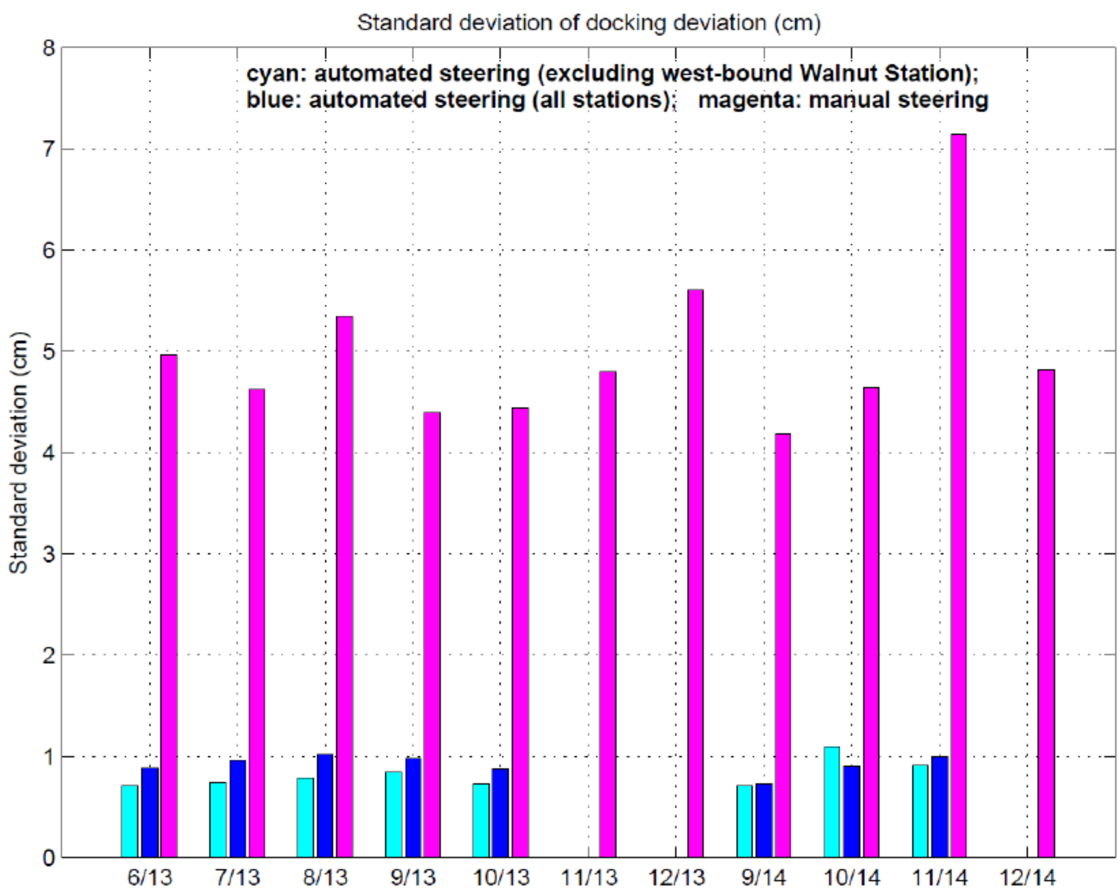

Figure 5-47

Standard deviation of docking deviation for each month of revenue service

[19]The precision docking at the WB Walnut Station yielded larger docking errors compared with that at the other five stations. Before entering the docking curve of the WB Walnut Station, the bus was driven at a relatively high speed on an expressway. Furthermore, the docking curve is so sharp that precision docking performance was loosened to allow a larger error to reduce the jerk and lateral acceleration for ride comfort.

Figure 5-48 compares the STD of the lateral accelerations (measured inside the instrument cabinet behind the front tire) under automated steering and that under manual driving for each month. Automated steering achieved STDs slightly smaller than manual steering, indicating that automated steering provided a slight advance in ride comfort to passengers.

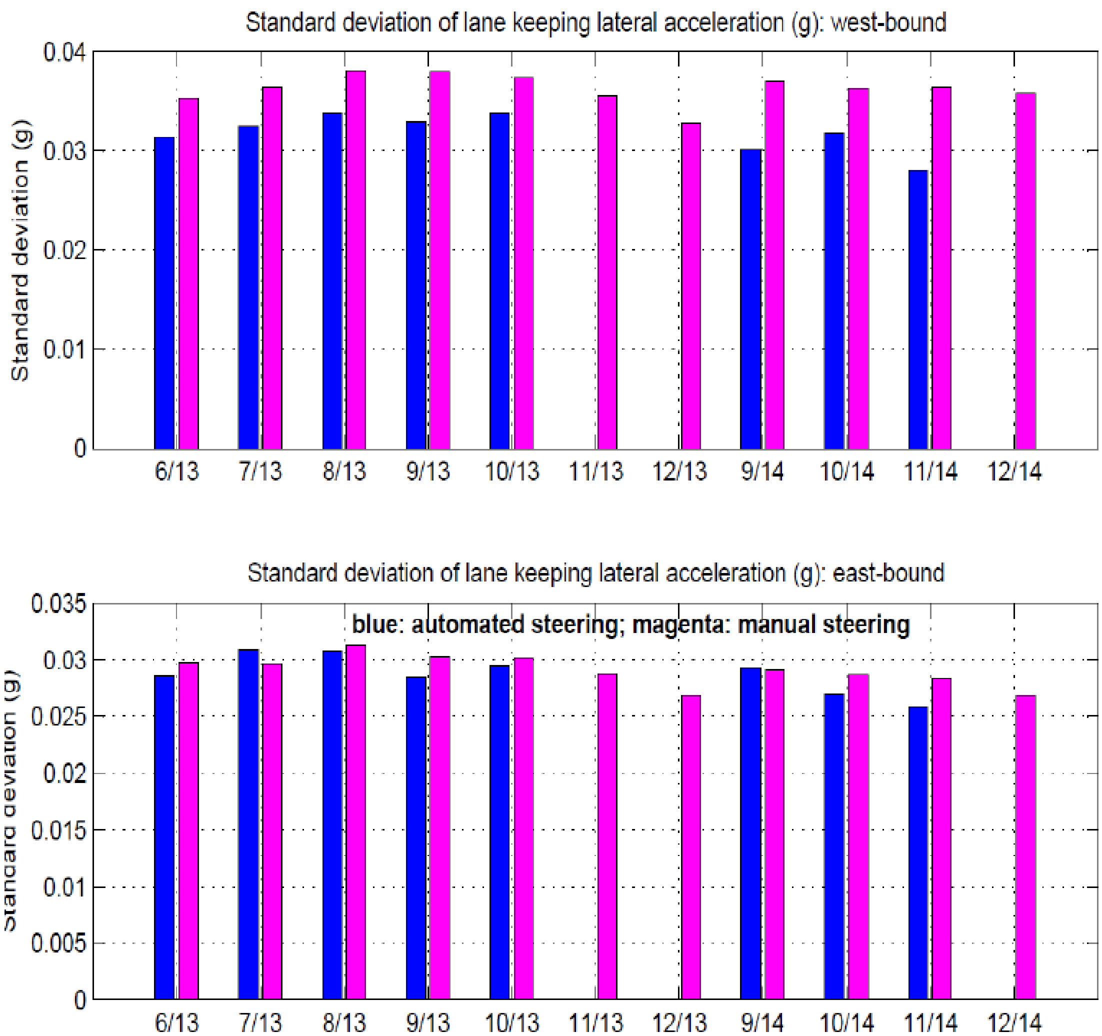

Figure 5-48

Standard deviation of lane-keeping lateral acceleration (g)

To evaluate how automated steering would affect operating speed, the EmX route was segmented to compute average speed in each segment. The main purpose of the segmentation was to remove dwell times at signalized intersections and at EmX stations. In general, the average speeds for each month were comparable with one another; there was no noticeable difference between the months with automated steering and the months with manual steering. As a result, the data indicate that there was no noticeable impact of automated steering on the general operating speed of the bus, which was controlled by the driver.

Fault Detection and Management

The VAA system itself did not experience system or component failure during revenue service operations. As a result, driver intervention due to VAA system fault did not occur during those periods. The VAA system, however, correctly detected faults (via monitoring bus J1939 CAN and sensor health) induced by the failure in the bus's own power system and warned the operator accordingly. On June 25, 2013, the VAA system detected faults in CAN communications and magnetic sensor bars twice. On the first occurrence, the bus was under manual steering; the VAA system lit the red LED light on the HMI as an indication. On the second occurrence, the bus was in automated steering mode and the VAA system provided an audible warning to the operator immediately. The operator then took over the control and the transition was smooth. LTD identified that the cause was a bad alternator and subsequently replaced it. Similar faults were detected again on July 24, July 29, August 2, and August 19, 2013. The VAA system detected the fault correctly all four times and provided warnings accordingly. In one of the four occurrences, the bus was under automation and the operator took over the control upon the warning; the transition from automated steering to manual steering was smooth and safe. LTD later identified that the recently-replaced alternator went bad and the battery failed as a result. Those incidences demonstrated that the VAA system was reliable and that system fault detection and management functioned correctly.

On average, the VAA system generated one false alarm per month. Those false alarms lasted less than 0.5 sec and created one short beep. Operators did not take any action given the short duration of the false alarms.

SECTION

6

Lessons Learned and Recommendations

This section presents the lessons learned through the lifecycle of the VAA demonstration project and provides recommendations based on those lessons.

Lessons Learned

The VAA project was one of the first vehicle automation and assist projects in the US that dealt with real-world deployment issues, including (a) new development of hardware and software for improved reliability and safety, (b) development process for product-like components and subsystems to meet the requirements of revenue services, (c) deployment issues such as project delivery, infrastructure, maintenance, and operational preparation, (d) close collaboration with transit agencies and bus operators during the development phase, (e) application and assessment of real-world operational scenarios, and (f) complexities in contractual arrangements with transit agencies and multiple industrial partners.

Safety is the first and most important design consideration for deploying an automated bus on a public roadway. When developing a safe VAA design, the first question to be answered was "is the system safe?" The answer should be that the automated bus will not create any hazardous situations to anybody inside or outside the vehicle. A safe design also means that the automated bus will safely handle all operational scenarios under all plausible environments, including the possibility of a faulty component or multiple components.

Safety of active safety systems or automated systems in a vehicle is still a new area in vehicle applications and, as such, consensus in its design has not been reached. The safety design of an automated bus system is likely not the same as that of an aviation or railroad automation system because of the specific constraints of low-cost, low-maintenance, and minimum operator training in the transit industry. Furthermore, the operating scenarios of a bus often put it in a state that the bus can encounter or create a hazardous situation in a fraction of a second. Therefore, designing a safe and economical system for an automated bus can be both an "art" and a systematic engineering process at the current state of automated vehicle technologies. Experienced and well-trained control engineers, system engineers, safety engineers, software engineers, hardware engineers, and test engineers are essential for developing and deploying such a safety-critical system at the current state of vehicle automation. A complementary team would need to be formed to leverage the individual knowledge and experience in automation and sensor technologies to deliver an economical and safe design that achieves the required the performance.

Redundancy is central to the safety and reliability of the VAA system. During development, it was determined that fault detection and warning are essential to safe operations. Another discovery was to design a degraded-mode control that is critical for keeping the bus under control until the operator can take over. The biggest challenge in vehicle automation is economical redundancy, which is to balance system redundancy and costs.

Safety design includes testing the automated system's ability to handle faulty conditions. Testing the ability to handle faults is a necessary but time-consuming process; however, it is critical to deploying a successful VAA system. Testing a bus on public roadways requires having a comprehensive fault detection and management system in place prior to the actual testing. Fault testing often uncovers issues that require software changes either in the field or in a laboratory environment. When any major revision of the VAA system software is performed, it requires the re-testing of the fault detection and management system to ensure safety while operating the VAA system. A good software interlocking mechanism is a way to safeguard mistakes in the fault testing procedure. The only safety-related incident that occurred during the entire VAA testing and revenue service period was the combination of two events: a control computer failed, and the degraded-mode control action was suspended because a "test version" of the software was improperly installed on the backup control computer. The fault was detected but the mitigation action was suspended. The PATH team installed an interlocking mechanism after the incident.

A comprehensive approach should be developed to streamline the design of the track layout when encountering any challenging road geometry, such as sharp curves or roadway obstructions. The method may need to combine surveying the roadway and track layout, with vehicle dynamics and driver behavior taken into consideration. Softness in ride feel and tightness in magnetic track following should be a tradeoff with respect to track layout, road geometry, possible range of measurement noises, operational speeds, and controller robustness.

Developing the VAA system for LTD was a learning process that leveraged control technologies and the experiences of transit operators. Although LTD bus drivers operated the VAA system, they discovered that the sensation was different than riding on a train even though the VAA system follows the magnet track like a train follows a rail track. The difference is in the design of the track each follows. A train track is typically designed with the speed of the vehicle in mind, whereas a bus track is typically designed with space or roadways in mind. This difference is very apparent in the curve sections of the two different tracks, which is why train tracks typically have much larger radii. During operations, some operators noted that the automatic steering actions changed the way they had to learn to drive the bus. A typical driver normally coordinates his speed control with his steering action and anticipates and prepares controlling the bus speed based on steering actions. Compared to the way a driver controls the bus, which is to look toward the horizon, the VAA automatic steering control system looks down at the trail of magnets embedded in the roadway. This means that a vehicle under VAA system control reacts to the roadway by "looking" at where it currently is rather than anticipating the geometry of the roadway ahead. Since the automated system exhibits different steering actions, bus drivers had to learn to adapt their speed while driving with the VAA system enabled. Each driver's confidence in the system reflected the way he related to operating it.

Safe operations are a requisite of any transit agency adopting bus driving assist and automation technology. Transit agencies should not test the automated system on public roadways if safe operations cannot be verified. Bus operators will not use the automated system if they have doubts about its safety and will turn it off. Since VAA systems are still in their early stages of development and deployment, it is the developer's role to ensure system safety and educate the transit agency about safe operations.

The results from the VAA LTD EmX testing suggest that operators generally liked the precision docking function. The VAA system maintained a consistent docking performance, and initial comments from the operators indicated that the VAA system reduced operator stress with improved performance. Drivers seemed to feel more comfortable about the safety record of the VAA bus after driving with the system enabled over a period of time.

Lateral acceleration data showed that most passengers would not feel the difference between the VAA system being enabled or disabled. However, a driver may feel that the ride is rougher under automatic control than it is under their control, as described earlier. It is important to note, however, that the EmX route was an "ultimate" test application of the technology because of the tight curves of the route in the Franklin corridor.

The lessons learned from LTD VAA revenue service testing indicate that an automated bus system should be designed to deal with faults that were not considered during the design and development phases. Following are three trouble-shooting examples, each after a bus operator reported a VAA system failure during revenue service operations:

- In April 2013, a driver reported two failures of the VAA system. The VAA system provided warning and then safely turned off the automatic function during the docking maneuvers. An analysis of the stored data indicated that someone had momentarily depressed the EMERGENCY button without engaging the switched safety lock. Further investigation revealed that the driver's left knee often touched the EMERGENCY button during the docking maneuver. The solution was to add a protective plate next to the button to prevent such occurrences from occurring in the future.
- The VAA system detected several intermittent faults during VAA operations in July 2013. The system provided warnings and maintained degraded-mode control

during this time frame. After the warnings were discovered, causes were found to be power supply problems from the bus: intermittent low voltage levels to the VAA sensors due to an alternator failure and a bad battery; a replacement alternator with a diode failure that created power glitches to the VAA system; and a video system damaged by the power failure that created power fluctuation that impacted part of the VAA system that connected to the same power terminal. All these discoveries led to better maintenance inspections of the bus and to future recommendations of looking at how power is supplied and emergency power supplies to the VAA system.

- In October 2014, a driver reported that the middle tire of the articulated bus might have touched the curb when approaching the WB Walnut Station. The data indicated that the bus had an additional 2 cm lateral movement toward the curb due to an unknown reason, which should have left 5 cm of clearance for the bus based on the surveyed data of that section of the curb. The PATH team performed an on-site manual measurement that revealed that there was a 5 cm discrepancy between the surveyed data and the true locations with respect to the magnets. LTD Maintenance also found out that a blown radius rod bushing caused a warp in the articulation joint that created the 2 cm lateral displacement. The bus was always 2 cm away from the curb at that location during the entire revenue service testing period. The PATH team modified the software to "move" the VAA system tracking 5 cm away on that location to ensure that it would not appear that the bus touched the curb.

There were multiple management lessons learned from the VAA project. Risk management across the board was important, including for contracts, liability, safety, technologies, resources, team availability, equipment, and support. Any one of those items could and often did cause delays in project delivery. As such, one major lesson learned was to have well-thought-out project planning and design from the start of the project and a realistic project schedule. The key to avoiding delays was to continuously identify and address issues as they appeared in safety, performance, costs, resources, operations, team availability, and contracting before they impacted delivery. Frequent and regular communications was the best solution to preventing and addressing delays. All phases in the life cycle of a VAA system product need to be considered and addressed.

Recommendations

This section presents recommendations for transit agencies in deploying a VAA system. The successful outcome of the VAA demonstration project was due to four major factors:

1. There must be a need for deploying a specific VAA application. For example, LTD needed precision docking for its EmX BRT system to provide consistent bus alignment during stops at stations to reduce driver stress and to eliminate

damage to buses and station platforms from collisions that occurred occasionally during manual docking maneuvers. VAA was able to address this need.

2. Sufficient resources must be available to develop and deploy such a system, both financially and in the way of support from management and decision-makers. In the case of the VAA demonstration project, funding and continued support from FTA and Caltrans were the key for success.
3. The technology needs to be available and a team ready to deliver it. In this project, PATH had almost 20 years of practical experience in vehicle automation and control systems.
4. The customer must be willing to provide its operational experience, facilities for testing, and support for deploying such a system. The support from LTD was critical to the successful deployment of the VAA system in revenue service operations and provided the real-world experience and feedback that bridged the gap between a prototype system and deployment-ready system for revenue service operations.

Along with the previous recommendations, it is critical to adopt safety standards in the design, development, and deployment process of a bus VAA system to ensure that the system is as safe as possible. Unfortunately, there were no standards available that address the safety issues specific to the automated system used in this VAA project. However, the ISO 26262 standard is a widely-accepted international automotive functional safety standard that defines functional safety for all activities during the lifecycle of safety-related systems comprising electrical, electronic, and software components; the VAA technical team went through the basic processes in ISO 26262 in defining the life cycle of the system, performing the hazard analysis, and determining the safety goals and safety concepts.

It is recommended by the PATH development team that the current VAA system should undergo one more design and development iteration to make it a commercially-viable solution for transit agencies. The VAA system was developed, designed, and built in 2009 and 2010 and uses components and technologies that are at least six years old as of this writing. An upgraded VAA system should focus on a safety-centered architecture, as well as efficient signal processing and control algorithms.

Once an upgraded VAA system is developed, any transit agency that wants to deploy its own system should work with a commercial partner. The advantages of using a commercial partner include the following:

- Efficient contractual procedures
- Clear liability framework
- Flexible design and operation
- Strong technical background
- Experience in vehicle safety and standards
- Ability to maintain and warranty the product

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APPENDIX

A

J1939 Message List for New Flyer 60-ft Diesel Articulated Bus

Electronic Retarder Controller #1

	Unit	Range	Updating Period
Enable brake assist status	Status		100ms
Actual retarder percent torque	Percent	-125 to +125	100ms

Electronic Brake Controller #1

	Unit	Range	Updating Period
EBS brake switch status	Status	0/1	100 ms
ABS active status	Status	0/1	100 ms
ASR brake control active status	Status	0/1	100 ms
ASR engine control active status	Status	0/1	100 ms
Brake pedal position	Percent	0 to 100	100 ms

Electronic Transmission Controller #1

	Unit	Range	Updating Period
Shift in process	Status		10 ms
Torque converter lockup engaged	Status		10 ms
Driveline engaged	Status		10 ms
Output shaft speed	RPM	0 to 8031.875	10 ms
Progressive shift disable	Status		10 ms
Input shaft speed	RPM	0 to 8031.875	10 ms

Electronic Engine Controller #1

	Unit	Range	Updating Period
Engine retarder torque mode	Integer		10ms-100ms
Driver demand percent torque	Percent	-125 to +125	10ms-100ms
Actual engine percent torque	Percent	-125 to +125	10ms-100ms
Engine speed	RPM	0 to 8031.875	10ms-100ms

Electronic Engine Controller #2

	Unit	Range	Updating Period
Kickdown active	Status		50 ms
Low idle	Status		50 ms
Accelerator pedal position	Percent	0 to 100	50 ms
Percent load current speed	Percent	0 to 125	50 ms
REMOTE accelerator position	Percent	0 to 199	50 ms

Electronic Transmission Controller #2

	Unit	Range	Updating Period
Selected gear	Integer	-125 to +125	100 ms
Actual gear ratio	Ratio (I/O)	0 to 64.255	100 ms
Current gear	Integer	-125 to +125	100 ms

Electronic Engine Controller #3

	Unit	Range	Updating Period
Nominal friction percent torque	Percent	-125 to +125	250 ms
Engine desired operating speed	RPM	0 to 8031.875	250 ms

Retarder Configuration

	Unit	Range	Updating Period
Retarder location	Integer	0 to 15	5000 ms
Retarder type	Integer	0 to 15	5000 ms
Retarder control steps	Integer	0 to 255	5000 ms

Engine Configuration

	Unit	Range	Updating Period
Engine speed	RPM	0 to 8031.875	5000 ms
Percent torque	Percent	-125 to +125	5000 ms
Reference engine torque	Nm	0 to 64255	5000 ms
Speed control lower limit	RPM	0 to 2500	5000 ms
Speed control upper limit	RPM	0 to 2500	5000 ms
Torque control lower limit	Percent	-125 to +125	5000 ms
Torque control upper limit	Percent	-125 to +125	5000 ms

Electronic Brake Controller #2

	Unit	Range	Updating Period
Front axle speed	m/sec	0 to 69.721	100 ms
Front left wheel relative	m/sec	-2.170 to +2.170	100 ms
Front right wheel relative	m/sec	-2.170 to +2.170	100 ms
Rear1 left wheel relative	m/sec	-2.170 to +2.170	100 ms
Rear1 right wheel relative	m/sec	-2.170 to +2.170	100 ms
Rear2 left wheel relative	m/sec	-2.170 to +2.170	100 ms
Rear2 right wheel relative	me/sec	-2.170 to +2.170	100 ms

APPENDIX

B

Component Test Results

This appendix presents the results of the testing of key components in the VAA system, including steering actuator, magnetic sensor module, DGPS/INS module, control computer, and HMI module. For each of these key components, the test results are presented with the features to be tested, test procedure, and acceptance criteria. Problems encountered during component testing and the corresponding debugging and resolutions are also provided.

Steering Actuator Test Results

The following table shows the features tested, the test procedure for conducting the specific test cases, and the corresponding acceptance criteria according to the component test plan for the steering actuator. The test results show that the steering actuator passed all acceptance criteria.

Features	Test Procedure	Acceptance Criteria	Test Results
Steering actuator sensor range, resolution, and accuracy	Command steering actuator motor such that steering wheel travels its whole range, record measurements of angular position sensor, examine measurements against motor specifications.	The angular position sensor(s) shall be able to measure the whole range of the steering wheel travel and be able to identify the absolute position of the steering wheel with accuracy and resolution within required specifications.	Passed. Both encoder and potentiometer measure full range of steering wheel travel (-825 deg to 825 deg). Resolution of encoder smaller than 0.2 deg and for potentiometer 1 deg.
Steering actuator torque capacity	Measure steering torque applied to steering column; examine measurements against motor specifications.	The Steering actuator shall be able to provide torque to the steering column and the torque capacity shall meet the specifications.	Passed. Steering actuator embedded processor provides torque command to steering actuator motor, and maximum torque capacity meets specifications.
Steering actuator mechanical design	Examine mechanical design of actuator assembly to ensure no modification made to steering column.	The Steering actuator assembly shall not reduce the mechanical property (e.g., the strength) of the original steering column.	Passed. No modification to existing steering column; steering actuator assembly would not reduce mechanical property of original steering column.
Steering actuator mechanical space	Measure mechanical space of steering actuator, compare with available space in bus; further install steering actuator into test bus and examine clearance.	The Steering actuator assembly shall fit the limited spaces available on the bus without interfering bus drivers' normal operation.	Passed.
Steering actuator mechanical assembly	Send commands of various patterns to steering actuator motor to extensively test steering actuator assembly; examine if any backlash developed or any vibration occurs; if so, measure size of backlash and frequency of vibrations.	The Steering actuator assembly shall not have excessive backlash or gap that generates vibrations of the assembly.	Passed.

Features	Test Procedure	Acceptance Criteria	Test Results
Steering actuator embedded processor	Test processor with data exchange rate (on interface) up to at least 5 times that in normal operation and computation cycle reduced to at least 1/5 of normal operation to evaluate processor throughput and processor speed capability.	The Embedded processor shall have throughput and processor speed that meet the specifications defined in the component developer's SOW.	Passed. Embedded processor shows consistently reliable performance with data exchange rate (on interface) at 5 times normal operation and computation cycle reduced to 1/5 of normal operation.
Steering actuator embedded processor interface	Connect steering actuator embedded processor to steering actuator motor's Electronic Control Unit (ECU) and control computer; verify data exchanges through interface.	The Embedded processor shall have sufficient I/O and data interface capabilities to interface with the DC motor's ECU, actuator sensors, and the control computer.	Passed.
Steering actuator power	Verify that steering actuator motor and embedded processor can operate with power from test bus.	The Steering actuator motor (including the motor's ECU) and the embedded processor shall satisfy the power specification for operating in the VAA bus.	Passed.
Steering actuator embedded processor working environment	After installing steering actuator in bus, connect steering actuator embedded processor to steering actuator motor's ECU (now in bus) and control computer in bus, verify interface, command motor ECU to steer steering wheel with various steering commands, monitor/ examine operation.	The Embedded processor shall work in the bus/ vehicle environment (electronically, mechanically, and environmentally).	Passed
Steering actuator embedded processor mechanical design	Repeatedly install/uninstall embedded processor, connect to and disconnect from steering actuator assembly and control computer, evaluate installation replacement procedure.	The Enclosure, mounting and connectors of the embedded processor shall be installable and replaceable by the transit technicians.	Passed

Several problems were encountered during the component testing for the steering actuator. First, backlashes were observed in the prototype steering actuator; the resolutions included modifying the material for the worm and ensuring a tight match between the worm and the steel worm gear.

Second, the steering actuator designed for the New Flyer bus could not be used for the MCI coach buses. Compared with the New Flyer bus, the MCI coach bus had a much tighter space for the steering actuator (due to its high-floor design), and its steering column was much more complicated. The steering actuator went through a complete redesign, and several iterations of fitting tests and design modifications to ensure that it fit into the MCI coach bus were made. The redesign included reducing the size of most components, reorienting the motor and sensors, and adding a two-dimensional U-joint.

Third, embedded software bugs were found to be responsible for problems including no reading from the motor encoder and inconsistency between the measurements from the motor encoder and those from the potentiometer. Resolutions included initializing the software drivers for the sensors and modifying the reading frequency of the motor encoder.

Magnetic Sensor Module Test Results

The following table shows the features tested, test procedure for conducting the specific test cases, and corresponding acceptance criteria according to the component test plan for the magnetic sensor module. The test results show that the magnetic sensor module passed all acceptance criteria.

Features	Test Procedure	Acceptance Criteria	Test Results
Magnetic sensor module sensing range, resolution, and accuracy	Place magnet at various locations within specified range, record magnetic sensor measurements, measure, record actual position of magnet, compare sensor measurements against actual positions of magnet to evaluate sensor range, resolution, accuracy, sampling frequency.	The Magnetic sensors shall measure the magnetic field with field strength range, total sensor range, resolution, accuracy and sampling frequency within required specifications.	Passed. Total sensor range for sensor module +/- 1.05 m, resolution 1mm. Sampling frequency of sensor above 250 Hz.
Magnetic sensor module consistency	Select a few fixed locations, place magnet at fixed locations several times, record sensor measurements, compare sensor measurements corresponding to same fixed locations to analyze consistency of measurements.	The Magnetic sensor module shall provide consistent field measurements under environmental conditions specified in the specifications.	Passed. Consistency of measurement for any fixed location within 5 mm.
Magnetic sensor module mechanical design	Test sensor module with water for waterproofness, subject sensor module to moderate oscillations and impacts more severe than typical during normal operation of bus, examine effects on magnetic sensor module.	The Mechanical assembly of the magnetic sensor module shall work in the bus/vehicle environment and most importantly it shall be water proof.	Passed.
Magnetic sensor module mechanical space	Install magnetic sensor module assembly at a few selected locations under test bus, evaluate sensor module's distance to side of bus and distance to ground.	The Magnetic sensor module assembly shall fit the limited spaces available under the bus frame.	Passed.
Magnetic sensor module embedded processor	Operate embedded processor with data exchange rate up to 3 times normal operation and computation cycle reduced to at least 1/3 of normal operation to evaluate processor throughput and processor speed capability	The Embedded processor shall have throughput, memory, and processor speed that meet the specifications defined in the developer's SOW.	Passed.

Features	Test Procedure	Acceptance Criteria	Test Results
Magnetic sensor module embedded processor interface	Connect sensor module embedded processor to control computer, evaluate data exchange through interface (e.g., no missing messages, no errors in data transmitted/received).	The Embedded processor shall have sufficient I/O and data interface capabilities to interface with the control computer.	Passed. Embedded processor can communicate to control computer at 50–100 Hz.
Magnetic sensor module power	After installing magnetic sensor module assembly under test bus, connect sensor module embedded processor to power from bus, verify sensor module can operate with power supply.	The Magnetic sensors and the embedded processor shall satisfy the power specification for operating in the VAA bus.	Passed.
Magnetic sensor module embedded processor environmental	After installing magnetic sensor module assembly under test bus, connect to control computer and power, verify operation of embedded processor in bus environment by driving bus along magnetic track, collect sensor measurements, evaluate sensor measurements.	The Embedded processor shall work in the bus/vehicle environment (electronically, mechanically, and environmentally).	Passed. Sensor module installed on New Flyer bus and tested on magnetic track at Richmond Field Station.
Magnetic sensor module calibration	After installing and interfacing magnetic sensor module, place magnet at various locations within specified range, record magnetic sensor measurements, measure and record actual position of magnet, compare sensor measurements against actual positions of magnet to evaluate sensor calibration.	The Magnetic sensor module shall be properly calibrated to remove/reduce errors due to the sensor installation misalignment.	Passed. Calibrated sensor module maintained 5 mm accuracy after installation.
Magnetic sensor module maintenance	Install/uninstall magnetic sensor module, connect to and disconnect from control computer, evaluate installation/replacement procedure.	The Enclosure, mounting and connectors of the embedded processor shall be installable and replaceable by the transit technicians with standard, commercially available tools.	Passed. Installation/uninstallation procedures straightforward and do not require special tools.

DGPS/INS Module Test Results

The DGPS/INS module for the VAA applications at AC Transit provided a robust, highly-accurate, and tightly-coupled DGPS/INS integration system.[20] The module included a DGPS base station and a DGPS/INS mobile unit, which consisted of one embedded computer, a dual-frequency GPS receiver, an Inertial Measurement Unit (IMU), a 900Mhz communication modem, a power module, and the associated antennae, software, and custom enclosure with cables and connectors.

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[20]The DGPS module for the VAA applications at LTD was an off-the-shelf commercial DGPS unit with differential signals from a Wide Area Augmentation System (WAAS). The DGPS module had already been operating on the test bus for a substantial period of time; therefore, component testing of this DGPS module was not in the scope of the component testing of the VAA project.

The following table shows the features tested, the test procedure for conducting the specific test cases, and the corresponding acceptance criteria according to the component test plan for the DGPS/INS module. The test results show that the DGPS/INS module passed all acceptance criteria.

Features	Test Procedure	Acceptance Criteria	Test Results
DGPS/INS module performance	Install DGPS/INS module on test vehicle, drive around, evaluate position data collected and stored by DGPS/INS module.	The DGPS/INS mobile unit shall receive and process the GPS and INS signals and provide bus positions with resolution, accuracy, and sampling frequency within the specifications in the developer's SOW.	Passed. DGPS/INS mobile unit provides position with better than 5 cm accuracy under ideal GPS conditions (with clear view of sky). resolution is 1 mm and update rate is 30 Hz.
DGPS/INS module base station	Install DGPS/INS module on test vehicle and drive around. Evaluate reception of differential signals from base station.	The DGPS base station shall broadcast differential data and the DGPS/INS mobile unit shall receive the differential data with the specifications in the component developer's SOW.	Passed.
DGPS/INS module consistency	Install DGPS/INS module on test vehicle, drive around fixed course, stop at several fixed locations. Evaluate accuracy of position readings.	The DGPS/INS module shall be able to provide consistent position measurements under environmental conditions as described in the specifications.	Passed. DGPS/INS module achieved better than 5 mm accuracy consistently under ideal GPS conditions.
DGPS/INS module message content	Connect GPS/INS module to control computer; evaluate data exchange through interface.	The DGPS/INS module shall provide at least the minimum message content as described in the component developer's SOW.	Passed. DGPS/INS mobile unit provides real-time position coordinates, operational status, accuracy measures, confidence index, etc.
DGPS/INS module mechanical design	Test DGPS/INS module exposed to bus external environment with water for its waterproofness, subject module to moderate oscillations and impacts more severe than typical during normal operation of bus, examine effects on module.	The DGPS/INS module mechanical assembly shall work in the bus/vehicle environment and in particular any module that is installed outside the bus shall be water proof.	Passed.
DGPS/INS module interface	Connect DGPS/INS module to control computer, evaluate data exchange through interface (e.g., no missing messages, no errors in data transmitted/received),	The DGPS/INS module shall have sufficient data interface capabilities to interface with the control computer as specified in the developer's SOW.	Passed. DGPS/INS mobile unit can communicate with control computer via either RS232 serial communication or Ethernet communication.
DGPS/INS module power	After installing DGPS/INS module on test bus, connect module to power from bus, verify module can operate with power supply.	The DGPS/INS module shall satisfy the power specification for operating in the VAA bus.	Passed.
DGPS/INS module maintenance	Install/uninstall DGPS/INS module, connect to and disconnect from its control computer, evaluate installation/ replace procedure.	The Enclosure, mounting and connectors of the DGPS/INS module shall be relatively easy to install and replace by the transit technicians.	Passed. Installation and replacement of DGPS/INS module straightforward and do not require special tools.

Control Computer

The following table shows the features tested, the test procedure for conducting the specific test cases, and the corresponding acceptance criteria according to the component test plan for the control computer. The test results show that the control computer passed all acceptance criteria.

Features	Test Procedure	Acceptance Criteria	Test Results
Control computer processor	Power up control computer, examine processor status, execute benchmark test programs.	The Control computer shall have throughput, memory, and processor speed that meet the specifications defined in the developer's SOW.	Passed.
Control computer software development environment	Power up control computer, connect to development PC, upload benchmark software and drivers, examine operating system performance, test software development environment including compile, build, and debug capabilities.	The Software development environment, the operating system, and the software drivers of the control computer shall satisfy the specifications in the developer's SOW.	Passed.
CAN interface	Connect control computers to other computers that simulate CAN communication of components that use CAN interface, check data interface capability.	The Control computer shall have sufficient data interface capabilities to connect to another control computer through CAN interface.	Passed.
CAN message throughput	Test CAN message rate up to 5 times rate for normal operation, record message loss and corruption if occur.	The CAN interface shall have throughput that meets the specifications defined in the developer's SOW.	Passed. Control computer does not lose any message with rate up to 200 Hz, (higher than 100 Hz normal rate).
Control computer mechanical design	Subject computers to moderate vibrations more severe than typical to bus interior in normal operations, test control computers in specified temperature range.	The Control computer mechanical assembly shall work in the bus/vehicle environment.	Passed.
Control computer power	Install control computers into test bus, connect to power from test bus, examine operation of control computer.	The Control computers shall satisfy the power specification for operating in the VAA bus.	Passed.
Control computer environment	After installing control computers in test bus and supplying with power, connect to J1939 CAN bus and other components, examine correctness of CAN messages received by and transmitted from control computers.	The Control computer and the associated CAN interface boards shall work in the bus/vehicle environment (electronically, mechanically, and environmentally).	Passed. Control computer correctly receives and transmits CAN messages on all four CAN interfaces simultaneously at specified rates.
Control computer maintenance	Install/uninstall control computers, connect to and disconnect from other components, evaluate installation/replacement procedure.	The Enclosure, mounting and connectors of the control computer shall be relatively easy to install and replace by the transit technicians.	Passed. Installation and replacement of control computer straightforward and do not require any special tools.

One issue encountered during the component testing for the control computers was the inconsistent power output from the control computer power supply. This problem was resolved by choosing power supplies that maintain their performance despite power fluctuations in the bus's electrical environment and by providing two independent power supplies, one for each control computer. Another issue related to the resource and timing of the multiple threads in the VAA program using multiple dedicated CAN bus communications; the priorities of the different threads and interrupts were carefully examined and re-set to ensure all the threads worked in harmony.

HMI Module

The following table shows the features tested, the test procedure for conducting the specific test cases, and the corresponding acceptance criteria according to the component test plan for the HMI module. The test results show that the HMI module passed all acceptance criteria.

Features	Test Procedure	Acceptance Criteria	Test Results
HMI module I/O	Turn on/off switches, examine HMI digital input readings, output 1 and 0 to each digital output, examine behavior of LED and sound devices.	The HMI module shall detect and accept all inputs from the switches, and control the digital outputs to all the LED and sound devices.	Passed.
HMI module mechanical design	Subject HMI module to moderate oscillations more severe than those typical to bus interior during bus operations, examine if HMI can operate normally under such conditions.	The HMI module mechanical assembly shall work in the bus/vehicle environment and be water resistant.	Passed.
HMI module mechanical space	Put HMI module at several candidate installation locations inside test bus, check clearance.	The HMI module assembly shall fit the limited spaces available in the bus.	Passed.
HMI module embedded processor	Operate embedded processor with data exchange rate up to 5 times normal operation and computation cycle reduced to at least 1/5 of normal operation to evaluate processor throughput and processor speed capability.	The Embedded processor shall have throughput, memory, and processor speed that meet the specifications defined in the developer's SOW.	Passed.
HMI module embedded processor interface	Connect HMI module embedded processor to control computer, verify data exchange through interface.	The Embedded processor shall have I/O and data interface capabilities for interfacing with the control computer.	Passed. Two HMI modules communicate with each other, two control computers through one CAN interface.
HMI module power	Install HMI module in test bus, connect to power from test bus, operation of HMI module.	The HMI module shall satisfy the power specification for operating in the VAA bus.	Passed.

Features	Test Procedure	Acceptance Criteria	Test Results
HMI module embedded processor environment	After installing HMI module in test bus and supplying with power, connect to control computer, examine data exchanges and control of LED and sound devices.	The Embedded processor shall work in the bus/vehicle environment (electronically, mechanically, and environmentally).	Passed. Two HMI modules can communicate with each other and two control computers through one CAN interface; two HMI modules control LED and sound devices as programmed.
HMI module maintenance	Install/uninstall HMI module, connect and disconnect from control computers, evaluate installation/replace procedure	The Enclosure, mounting and connectors of the embedded processor shall be relatively easy to install and replace by the transit technicians.	Passed.

APPENDIX

C

Component Integration Test Results

This appendix presents the results of the integration testing for each of the five major components, including the steering actuator, magnetic sensor modules, DGPS/INS module, HMI modules, and control computers and the existing mechanical, electrical, and data communication systems of the transit buses that are interfaced with the above VAA components. For each of the key components, three categories of the interface were examined: mechanical installation, electrical power supply, and data communication. The relevant features and acceptance criteria, problems encountered during component integration testing, if any, and the corresponding debugging and resolutions are provided.

Steering Actuator

The following table shows the features tested, the test procedure for conducting the specific test cases, and the corresponding acceptance criteria according to the component integration test plan for the steering actuator. The test results verify that the steering actuator passed all acceptance criteria.

Features	Test Procedure	Acceptance Criteria	Test Results
Mechanical space	Measure mechanical space of steering actuator and compare with available space in bus; after installing steering actuator into test bus, examine clearance.	The Motor and its associated gear system shall be small enough to fit in the limited space under the dashboard, and the motor assembly shall allow adequate space to ensure the driver can comfortably drive the bus.	Passed.
Friction and free-play	Turn steering wheel, examine friction and free-play.	The Installation of the steering actuator shall not create excessive hard nonlinearities such as friction and free-play.	Passed. Steering wheel turns easily and smoothly, free-play is 2–3 deg.
Steering actuator power	Verify that steering actuator motor and embedded processor can operate with power from test bus.	The Steering actuator shall use the existing bus DC power supply and provide enough electrical power so that the steering actuator can generate the required torque for operation.	Passed.
Steering actuator power usage	Measure voltages of bus battery while steering actuator is on/off, verify that voltages do not change more than 1 volt.	The Power usage of the steering actuator shall not create power surges affecting the existing vehicle electrical systems.	Passed. No observable changes in voltages of bus battery.

Features	Test Procedure	Acceptance Criteria	Test Results
Steering actuator message content	Store data communicated to control computers from steering actuator, verify that 1) data received by control computers contain required data contents, 2) data follow designed data format, 3) values of data received are consistent with values sent by steering actuator.	The Steering actuator shall provide message ID, status, actuator health signal, and fault messages to the control computers. The steering actuator shall also provide actuator measurements to the control computers.	Passed. Stored data at control computers show that CAN messages from actuator in designed format and received at designated frequency.
Control computer message content	Store data from control computers to steering actuator, verify that data received by steering actuator contain required data contents and format, values of data received are consistent with that sent by control computers.	The Control computer shall provide message ID, mode command, and the corresponding actuator angle and torque commands to the steering actuator.	Passed. Steering actuator indicates that CAN messages from control computers were received at designed frequency and they include all required content.
Data communication rate	Store data communicated between control computers to steering actuator on both sides, verify communication rate and reliability.	The Steering actuator and the control computer shall communicate the data at an update rate specified by the interface requirements without message drop or data error.	Passed. Control computers and steering actuator sent and received messages from other party as designed.
Steering actuator capabilities	Verify that steering actuator capabilities in sensor range, resolution, accuracy, and torque capacity by following test procedure described in component test plan: 1) command steering actuator motor such that steering wheel travels its whole range, record measurements of angular position sensor, examine measurements against motor specifications, 2) measure steering torque applied to steering column, examine measurements against motor specifications.	The Installed steering actuator shall maintain its corresponding component performances after it is installed onto the bus and connected to the control computer. The angular position sensor(s) shall be able to measure the whole range of the steering wheel travel and be able to identify the absolute position of the steering wheel with accuracy and resolution within required specifications. The Steering actuator shall be able to provide torque to the steering column and the torque capacity shall meet the specifications.	Passed. Encoder and potentiometer measure full range of steering wheel travel and maintained designed resolution. Steering actuator embedded processor provides torque command to steering actuator motor, and maximum torque capacity rated torque.
Steering actuator performance	Verify steering actuator closed-loop servo performance: 1) control computers send various steering angle commands to steering actuator, 2) read and store steering angles measured by steering angle sensors, 3) examine closed-loop bandwidth, rate and accuracy of response against steering actuator specifications.	The Integrated steering actuator with its baseline servo control software shall achieve the steering actuator performances requirements specified by the VAA system requirements.	Passed. Steering actuator achieved better than 1 deg accuracy at steering wheel with 3–5 Hz bandwidth, as specified in VAA system requirements.

Magnetic Sensor Module

The following table shows the features tested, the test procedure for conducting the specific test cases, and the corresponding acceptance criteria according to the component integration test plan for the magnetic sensor module. The test results demonstrate that the magnetic sensor module passed all acceptance criteria.

Features	Test Procedure	Acceptance Criteria	Test Results
Mechanical space	After installing magnetic sensor module assembly under test bus, examine sensor modules' distance to side of bus and distances to ground.	The Magnetic sensor modules shall be installed under the bus body frame, fit the limited spaces available under the bus frame, and provide sufficient clearance between the ground and the bus body frame.	Passed.
Magnetic field interference	Examine distance from magnetic sensor modules to locations of bus components (such as wheels) that could potentially interfere with magnetic fields to be measured by sensor modules, place magnet at various locations within specified range, record magnetic sensor measurements, measure, record actual position of magnet, compare sensor measurements against actual positions of magnet to evaluate interference from bus components.	The Magnetic sensor modules shall be installed in such a way that any interference by the vehicle's own magnetic fields shall not degrade the accuracy of the position measurement to below the specifications.	Passed. Mounting locations of sensor modules chosen carefully to be away from vehicle components (such as tires) that could impose magnetic interference.
Working environment	Drive test bus to subject sensor module to moderate oscillations and impacts typical during normal operation of bus, examine their effects on magnetic sensor module, test sensor module including connectors and wiring with water for waterproofness.	The Magnetic sensor module assembly shall work in the bus/vehicle environment and any external component shall be water proof.	Passed.
Magnetic sensor module maintenance	Install/uninstall magnetic sensor modules, connect to and disconnect from control computers, evaluate installation/replace procedure.	The Enclosure, mounting and connectors of the magnetic sensor module shall be relatively easy to install and replace; that is, the enclosure, mounting and connectors of the magnetic sensor module shall be installable and replaceable by the transit technicians with standard, commercially available tools.	Passed. Install/uninstall of magnetic sensor module straightforward and do not require special tools.

Features	Test Procedure	Acceptance Criteria	Test Results
Electrical and power supplier	After installing magnetic sensor modules under test bus and connecting sensor module embedded processors to power from bus, verify sensor module operates with power supply; drive bus along magnetic track, collect sensor measurements, evaluate sensor measurements to verify operation of magnetic sensor module in bus environment.[21]	The Magnetic sensor module shall use the existing DC power supply from the bus. The power fluctuations of the bus during normal bus operation shall not degrade the measurement accuracy of the magnetic sensor module.	Passed.
Magnetic sensor module message content	Store data communicated to control computers from magnetic sensor modules, verify that 1) data received by control computers contain required data contents, 2) data follow designed data format, 3) values of data received are consistent with values sent by embedded processors of magnetic sensor modules.	Each magnetic sensor module shall provide the sensor ID, status, fault message, health signal to the control computer. Each magnetic sensor module shall also provide the lateral position measurements to the control computer.	Passed. Stored data at control computers shows that CAN messages from magnetic sensor modules in designed format and received at designated frequency; CAN messages included all required content.
Control computer message content	Store data communicated from control computers to magnetic sensor modules, verify that 1) data received by embedded processors of magnetic sensor modules contain required data contents, 2) data follow designed data format, 3) values of data received are consistent with values sent by control computers.	The Control computer shall provide the magnetic sensor module with sensor mode command as well as other required operational data.	Passed. Magnetic sensor modules receive CAN messages from control computers at designed frequency and messages include all required content.
Data communication rate	Store data communicated between control computers to magnetic sensor modules on both sides, verify communication rate and reliability.	The Magnetic sensor module and the control computer shall communicate the required data at an update rate as specified by the interface requirements without message drop or data error.	Passed. Both control computers and magnetic sensor modules send and receive messages from other party as designed.
Performance evaluation of magnetic sensor modules	Place magnet at various locations within specified range, record magnetic sensor measurements, measure and record actual position of magnet, compare sensor measurements against actual positions of magnet to evaluate sensor range, resolution, accuracy, sampling frequency; select a few fixed locations, place magnet at fixed locations several times, record sensor measurements, compare sensor measurements corresponding to same fixed locations to analysis consistency of measurements.	The Magnetic sensor modules shall maintain the component performances criteria for passing the component testing of the magnetic sensor module when it is installed under the bus and communicates with the control computer. Such performance criteria include specifications for field strength range, total sensor range, resolution, accuracy and sampling frequency, as well as consistent measurements under environmental conditions specified in the specifications.	Passed. Sensor measurement resolution is 1mm, consistency of measurement for any fixed location also within 5 mm. Sensing range for magnetic sensor module is -105 cm to 105 cm with respect to center of sensor module.

[21]The robustness and performance of the magnetic sensor modules were continuously evaluated during the component integration testing and subsequent system testing and operational testing to ensure the reliability and accuracy of the magnetic sensor module.

Features	Test Procedure	Acceptance Criteria	Test Results
Magnetic sensor module calibration	Place a magnet at various locations within specified range, record magnetic sensor measurements, measure and record actual position of magnet, compare sensor measurements against actual positions of magnet to evaluate sensor calibration.	The Magnetic sensor module shall be calibrated to account for the static magnetic influence from the bus frame, body as well as other close-by bus components.	Passed. Calibrated sensor module maintained 5 mm accuracy after installation.
Magnetic sensor module performance	Verify performance of magnetic sensor basic signal processing software: 1) drive test bus through test track with magnets installed under pavement, 2) receive and store lateral deviation from magnetic sensor modules (lateral deviation processed by embedded processors based on magnetic field strength measured by magnetic sensors), 3) examine smoothness and accuracy of lateral measurements against magnetic sensor module performance specifications.	The Magnetic sensor module with its baseline signal processing software shall achieve the lateral sensing performances requirements specified by the VAA system requirements when it is installed onto the bus and connected to the control computer.	Passed. Due to interference of shallow and dense re-bars on track, lateral position accuracy achieved is about 1~2 cm, still within performance requirements.

A main problem encountered during the component integration testing for the magnetic sensor module was in the CAN communication between the magnetic sensor modules and the control computers; high drop rates of CAN messages were observed. The problem was improper termination on the CAN node. Hardware corrections were made to resolve this issue.

DGPS/INS Module

The following table shows the features tested, the test procedure for conducting the specific test cases, and the corresponding acceptance criteria according to the component integration test plan for the DGPS/INS module. The test results show that the DGPS/INS module passed all acceptance criteria.

Features	Test Procedure	Acceptance Criteria	Test Results
Mechanical installation	After installation, check location of GPS antenna and height of other parts of DGPS/INS mobile installed on bus roof.	The GPS antenna of the DGPS/INS mobile unit shall be installed on the bus roof; any other part of the DGPS/INS mobile, if installed on the bus roof, will be of low profile to minimize the wind resistance.	Passed.
DGPS/INS module mechanical design	Test DGPS/INS components installed outside bus (such as GPS antenna) with water for waterproofness, drive bus to subject module to oscillations and impacts typical during normal operation of bus and examine effects on module.	The DGPS/INS module mechanical assembly shall work in the bus/vehicle environment and any external component shall be water proof.	Passed.

Features	Test Procedure	Acceptance Criteria	Test Results
DGPS/INS module maintenance	Install/uninstall DGPS/INS mobile unit, connect to and disconnect from control computer, evaluate installation/ replace procedure.	The Enclosure, mounting and connectors of the DGPS/INS mobile unit shall be relatively easy to install and replace.	Passed. Installation and replacement of DGPS/INS mobile unit straightforward and do not require special tools.
DGPS/INS module power supply	After installing DGPS/INS mobile unit on test bus, connect module to power from bus, verify module can operate with power supply and not affected by power fluctuations.	The DGPS/INS mobile unit shall satisfy the power specification for operating in the VAA bus. The Power fluctuations of the bus during normal bus operation shall not degrade the measurement accuracy of the DGPS/INS module.	Passed. DGPS/INS mobile unit maintains performance and not affected by power fluctuation of bus.
DGPS/INS module message content	Store data communicated to control computers from DGPS/INS module, verify that 1) data received by control computers contain required data contents, 2) data follow designed data format, 3) values of data received are consistent with values sent by embedded processor of DGPS/INS module.	The DGPS/INS module shall provide the time stamp, status, health signal to the control computer. The DGPS/INS module shall also provide the lateral position measurements (absolute and/ or relative), with the associated confidence parameters to the control computer.	Passed. Stored data at control computers show messages from DGPS/INS mobile unit in designed format and received at designated frequency; messages include all required content such as time stamp, status, position measurements, confidence, health signal, etc.
Data communication rate	Store data communicated from DGPS/INS mobile unit to control computers, verify communication rate and reliability.	The DGPS/INS mobile unit shall communicate the required data at an update rate as specified by the interface requirements without message drop or data error.	Passed. DGPS/INS mobile unit communicates required data at required 10 Hz.
DGPS/INS module operational performance	Drive test bus around fixed course, stop at several fixed locations, evaluate accuracy and consistency of position readings.	The Integrated DGPS/INS mobile unit shall maintain the component performances criteria (i.e., resolution, accuracy, sampling frequency) for passing the component tests of the DGPS/ INS module.	Passed. Integrated DGPS/ INS mobile unit maintained performance after installation.
DGPS/INS module base station	Drive test bus around, evaluate position data collected and stored by DGPS/INS mobile unit.	The Integrated DGPS/INS mobile unit shall receive the differential signals from the GPS base station through the designated communication means.	Passed.
DGPS/INS module positioning performance	Verify performance of DPGS/ INS positioning software: 1) drive test bus through test track with magnets installed, 2) read and store DGPS/INS and lateral positions from magnetic sensor modules, 3) compare smoothness, consistency, accuracy of DGPS/INS positions with those of lateral positions from magnetic sensor modules, 4) examine resultant DPGS/ INS positions against DGPS/ INS module performance specifications.	The Integrated DGPS/INS module with its baseline positioning software shall achieve the lateral positioning performances requirements specified by the VAA system requirements.	Passed. DGPS/INS mobile unit achieved better than 5 cm accuracy under ideal GPS conditions with clear view of sky.

HMI Module

For the VAA project, two HMI modules were used for redundancy purposes. The following table shows the features tested, the test procedure for conducting the specific test cases, and the corresponding acceptance criteria according to the component integration test plan for the HMI modules. The test results verify that the HMI modules passed all acceptance criteria.

Features	Test Procedure	Acceptance Criteria	Test Results
HMI module mechanical space	Sit in driver seat, check clearance, drive bus, check if HMI modules interfere with manual operations.	The HMI modules shall be installed in the bus interior within the space limitations and shall not interfere with the manual operations of the driver.	Passed.
HMI device accessibility	Sit in driver seat, check accessibility of HMI devices by turning on/off switches, observing changes in LEDs, drive bus, check accessibility of HMI devices during operation.	The HMI devices shall be located within the areas accessible to the bus operator. The Switches for drivers to turn on or off shall be installed at locations easily reachable by the drivers while the LEDs shall be at locations visible to the drivers. The Sound devices are preferred to be installed close to the driver so as to limit their effect on the passengers.	Passed. Both on/off switches and kill switch easily reachable by driver. Location of LED and sound devices chosen with inputs from participating transit agency; LEDs easily visible to drivers and sound clear to drivers.
HMI module mechanical design	Drive bus to subject HMI module to oscillations typical to bus interior during bus operations, examine if HMI modules can operate normally under such conditions.	The HMI module shall work in the bus/vehicle environment.	Passed.
HMI module maintenance	Install/uninstall HMI modules, connect to and disconnect from control computers, evaluate installation/replace procedure.	The Enclosure, mounting and connectors of the HMI modules shall be relatively easy to install and replace.	Passed. Installation and replace procedures straightforward, no special tools required.
HMI module power	Turn on/off HMI modules, examine operation of HMI modules, check power input of redundant components of HMI modules.	The HMI module shall use the existing DC power supply from the bus, and the power fluctuations of the bus during normal bus operation shall not degrade the process and HMI devices performance and reliability.	Passed. HMI devices performance not affected by power fluctuations of bus.
HMI module I/O	Turn on/off switches, examine digital input readings of HMI modules; have HMI modules output 1 and 0 to each of digital outputs, examine behavior of LEDs and sound device.	The HMI modules shall read the driver requests from the HMI devices and communicate with the control computers as specified by the interface requirements.	Passed. HMI modules read HMI switch inputs as designed, LED, sound devices behave correctly according to commands from HMI module.

Features	Test Procedure	Acceptance Criteria	Test Results
HMI module message content	Store data communicated to control computers from HMI module, verify that 1) data received by control computers contain required data contents, 2) data follow designed data format, 3) values of data received consistent with values sent by embedded processors of HMI modules.	The HMI module shall provide the module ID, status, fault messages, health signal to the control computer. The HMI module shall also provide driver commands according to the inputs from the HMI devices to the control computer.	Passed. Stored data at control computers show messages from HMI modules in designed format and received at designated frequency; messages include all required content such as module ID, status, fault messages, health signal, etc.
HMI module feedback to driver	Program HMI modules' embedded processors to provide various feedbacks to driver and evaluate quality of feedback signals.	The HMI module shall provide clear feedback to the operator, as well as clear information and command to the driver whenever the system requires an action from the driver in real-time as specified by the interface requirements.	Passed. Sound device provides some distinctly different sound patterns for warnings (indicating emergency situations, system faults), acknowledgement of driver inputs. LED devices clearly indicate status of system.
Control computer message content	Store data communicated from control computers to HMI modules, verify that 1) data received by embedded processor of HMI module contain required data contents, 2) data follow designed data format, 3) values of data received are consistent with values sent by control computers.	The Control computer shall provide ID, system operational status, fault messages, and health signal to the HMI module.	Passed. Data received by HMI module from control computer contain all required information including message ID, system operational status, fault messages, and health signal.
Data communication rate	Store data communicated between HMI modules and control computers on both sides, verify communication rate and reliability.	The HMI module and the control computer shall communicate the required data at an update rate as specified by the interface requirements without message drop or data error.	Passed. Two HMI modules and control computers communicate with one another at specified rate without message drop or data error.
HMI module operational performance	Operate embedded processor with data exchange rate up to 5 times normal operation, computation cycle reduced to at least 1/5 of normal operation to evaluate processor throughput and processor speed capability.	The Integrated HMI modules shall maintain the component performances criteria (e.g., the embedded processor throughput, memory, and processor speed) for passing the component testing of the HMI module when they are installed in the bus and communicates with the control computer.	Passed. Integrated HMI modules maintain performance after installed in test bus.

Vehicle CAN Interface

The following table shows the features tested, the test procedure for conducting the specific test cases, and the corresponding acceptance criteria according to the component integration test plan for the vehicle CAN interface. The test results verify that the CAN interface passed all acceptance criteria.

Features	Test Procedure	Acceptance Criteria	Test Results
Mechanical installation	Check CAN interface controller board installation and wiring. Turn on control computers, start engine, check whether control computer receives vehicle J1939 CAN messages via CAN interface.	The CAN interface controller boards shall be installed inside the control computers and connected to the existing CAN port in the bus with proper wiring, shielding and termination. The CAN interface controller board shall work in the bus/vehicle environment.	Passed. Control computer receives vehicle J1939 CAN messages via CAN interface.
Electrical installation	Check CAN interface controller physical layer isolation and CAN termination.	The CAN interface controller physical layer shall contain isolation from the control computer as well as between ports (since 2-port CAN interfaces are used) for both externally and internally powered CAN interface. The Transmission line of the CAN interface controller shall be properly terminated.	Passed.
Message content and communication rate	Turn on bus, drive around, store data received from vehicle J1939 CAN bus while bus running; check stored data to verify 1) data received contain required data contents, 2) rate of data received looks reasonable and corresponding resolutions are correct.	The CAN interface shall provide the engine/transmission states of the bus that are required by the VAA system operations through J1939 in-vehicle data networks with sufficiently update rate as specified by the interface requirements.	Passed. Vehicle CAN messages provide all required engine and transmission states, vehicle CAN messages updated and received at 10 Hz, which satisfies interface requirements.
Operational performance	Turn on bus, drive around with all other CAN communication channels (magnetic sensors, steering actuators, HMIs) on, store data received from vehicle J1939 CAN bus while bus running; check stored data to verify 1) data received contain required data contents, 2) values of data received look reasonable, 3) error rate is within specifications.	The Integrated communications between the existing J1939 CAN networks through the CAN interface with the control computer shall maintain the interface performance specified by the interface requirements when they are installed and connected in the bus operating environment.	Passed.

Control Computer

The VAA system consists of two control computers as the core processor, which host the key software functional modules and maintain the main data communication channels of the VAA system. Each control computer communicates with the steering actuator, magnetic sensor modules, DGPS/INS module, HMI, and existing J1939 CAN networks in the bus, as well as the other control computer.

The following table shows the features tested, the test procedure for conducting the specific test cases, and the corresponding acceptance criteria according to the component integration test plan for the control computers. The test results verify that the control computers passed all acceptance criteria.

Features	Test Procedure	Acceptance Criteria	Test Results
Mechanical space	Examine clearance around control computers; drive test bus around with control computers turned on; bus operation must exhibit same characteristics as when control computers are off.	The Control computers shall be installed in the bus interior within the space limitations and shall not interfere with other existing electronic systems in the bus.	Passed.
Mechanical design	Drive test bus to subject control computers to moderate vibrations typical to bus interior during normal operations; test control computers in specified temperature range.	The Control computer assembly shall work in the bus/vehicle environment.	Passed. Control computers perform well in bus/vehicle environment and not affected by moderate vibrations typical to bus interior.
Control computer maintenance	Install/uninstall control computers, connect to and disconnect from other components, evaluate installation/replace procedure.	The Enclosure, mounting and connectors of the control computers shall be relatively easy to install and replace.	Passed. Installation and replacement of control computers straightforward and do not require any special tools.
Control computer electrical and power supply	Turn on/off control computers, examine operation of control computers. Check power supplies to control computers to make sure independent.	The Control computers shall use the existing DC power supply from the bus, and each control computer shall have a separate power input. The Power fluctuations of the bus during normal bus operation shall not degrade the processors' performance and reliability.	Passed.
Control computer message content	Store data sent and received by both control computers, compare stored data to verify that 1) data contain required data contents, 2) values of data received are consistent with data sent.	Each control computer shall provide to the other control computer with its ID, status, mode, health signal, fault messages as well as the real time commands.	Passed. Each control computer can receive CAN message from other control computer at specified rate; received CAN message consists of all required contents.

Features	Test Procedure	Acceptance Criteria	Test Results
Control computer communication rate	Turn on all components including control computers, steering actuator, magnetic sensor modules, DGPS/INS mobile unit, HMI modules, test bus (to start J1939 CAN bus), examine rate and correctness (i.e., no missing messages, no errors in data) of CAN messages received by and transmitted from control computers.	For the data communication between the two control computers and other components (as described in Sections 4.1 to 4.5), the added communication between the two control computers shall keep the original data communication channel with sufficiently high update rate as specified by the interface requirements.	Passed. Two control computers send CAN messages to and receive CAN messages from each other at specified rate of operation.
Control computer operational performance	Turn on all components, follow procedure specified in component testing plan to 1) check control computer processor performance (throughput, memory, speed), 2) install and modify software using software development environment, 3) store data received by CAN messages, 4) send test messages and/or commands to various embedded processors.	The Integrated control computers shall maintain the component performances criteria for passing the component testing of the control computers when it is installed under the bus and communicates with each other.	Passed. Each control computer maintains its performance after installed in bus.

Integration of Subsystems

Component integration testing was conducted in a bottom-up fashion following a hierarchical process—two components were first combined into an integrated subsystem, and the interface between them was tested. Subsequently, two subsystems were then combined into a larger subsystem, and the component integration testing was conducted on the larger subsystem. The idea was to expand the process to test larger subsystems with subsystems that had been tested. Eventually, all subsystems making up the VAA system were tested together.

The following table shows the features tested, the test procedure for conducting the specific test cases, and the corresponding acceptance criteria according to the component integration test plan for combined subsystems. The test results verify that all key subsystems, their installation on the bus, and their appropriate interfaces satisfied all acceptance criteria.

Features	Test Procedure	Acceptance Criteria	Test Results
Mechanical installation	Visually examine installation of subsystems to detect interference between them, check clearance around each subsystem, drive bus, check for interference to normal operations from installed subsystems.	Any two to all sub-systems' installation shall not interfere with each other and shall not degrade the normal bus operations.	Passed.
Power Supplier	Turn on/off subsystems, measure voltages of bus battery to examine effect on bus electrical systems, measure power to each subsystem to detect interference.	Any two to all subsystems' power usages combined shall not degrade the normal bus electrical systems performance. Any two to all subsystems' power combined shall not interfere with each other.	Passed. No interference detected.
Electrical installation	Examine wiring of all subsystems to verify proper wiring and shielding, measure terminations, use scope to verify all digital grounds connected, all power grounds connected, digital grounds and power grounds are separate.	The Transmission line of the each and all communication lines, including the CAN data lines shall be properly wired, shielded and terminated so that no interference among any sub-systems as well as with any existing vehicle systems.	Passed.
Data communication with steering actuator	With any or all other subsystems running at same time, store data communicated between control computers and steering actuator on both sides, verify that 1) data received by control computers from steering actuator and data received by steering actuator from control computers contain required data contents, 2) data follow designed data format, 3) values of data received consistent with values sent, 4) communication rate is as specified by interface requirements.	The Control computer shall provide the steering actuator with the proper actuator commands as well as the health and status messages with sufficiently high update rate as specified by the interface requirements. The Control computer shall receive from the steering actuator its ID, status, state, mode, health signal, fault messages as well as the real time measurements with sufficient update rate as specified by the interface requirements.	Passed. Performance of data communication between control computers and steering actuator not affected by other VAA components.
Data communication with magnetic sensor modules	With any or all other subsystems running at same time, store data communicated between control computers and magnetic sensor modules on both sides, verify that 1) data received by control computers from sensor modules and data received by embedded processors of sensor modules from control computers contain required data contents, 2) data follow designed data format, 3) values of data received consistent with values sent, 4) communication rate is as specified by interface requirements.	The Control computer shall provide the magnetic sensor module with sensor mode command as well as other required operational data and operational status with sufficiently high update rate as specified by the interface requirements. The Control computer shall receive from the magnetic sensor module its ID, status, health signal, fault messages as well as the real time measurements with sufficient update rate as specified by the interface requirements	Passed. Performance of data communication between magnetic sensor modules and control computers not affected by other VAA components.

Features	Test Procedure	Acceptance Criteria	Test Results
Data communication with DGPS/INS module	With any or all other subsystems running at same time, store data communicated from DGPS/INS mobile unit to control computers, verify that 1) data received by control computers contain required data contents, 2) data follow designed data format, 3) values of data received consistent with values sent, 4) communication rate is as specified by interface requirements.	The Control computer shall receive from the DGPS/INS module its ID, status, health signal, as well as the real time measurements with the associated confidence parameters with sufficient update rate as specified by the interface requirements.	Passed. Data communication with DGPS/INS module maintains its performance and not affected by other VAA components.
Data communication with HMI modules	With any or all other subsystems running at same time, store data communicated between control computers and HMI modules on both sides, verify that 1) data received by control computers from HMI modules and data received by embedded processors of HMI modules from control computers contain required data contents, 2) data follow designed data format, 3) values of data received consistent with values sent, 4) communication rate is as specified by interface requirements.	The Control computer shall provide the HMI module with driver command and feedback with sufficiently high update rate as specified by the interface requirements. The Control computer shall receive from the HMI module its ID, status, health signal, fault messages as well as the real time driver requests with sufficient update rate as specified by the interface requirements.	Passed. Data communication between control computer and HMI modules not affected by other VAA components.
Data communication with J1939 vehicle CAN bus	With any or all other subsystems running at same time, store data control computer received from J1939 vehicle CAN bus, verify that 1) data received by control computers contain required data contents, 2) values of data received are reasonable and correct, 3) communication rate is as specified by interface requirements.	The Control computer shall receive from the CAN interface the engine/transmission states of the bus through the J1939 in-vehicle data networks with sufficient update rate as specified by the interface requirements.	Passed. Communication with J1939 vehicle CAN bus maintains its performance and not affected by other VAA components.
Data communication rate	With all subsystems running at same time, check communication rate on each of above channels to verify that communication rates satisfy interface requirements.	The Simultaneous data communications for any number of the above channels (until all can be simultaneously send and receive) shall be satisfied with sufficient update rate as specified by the interface requirements.	Passed. All data communication can work simultaneously, each maintains its performance at specified rate without being affected by other VAA components.
Component operational performance	With all subsystems running at same time, 1) store and verify data communicated between control computers, magnetic sensor modules, HMIs and steering actuator are within specifications, 2) send commands from control computers to steering actuator and HMI modules and verify response are within specifications.	The Integrated control computers shall maintain the component performances criteria for passing the component testing of the control computers when it is installed under the bus and communicates with any two to all key VAA sub-systems.	Passed. With all subsystems running at same time, each VAA component maintains its own component performance and communication with other components satisfies interface requirements.

APPENDIX

D

University of California VAA Human Factor Study Consent Form

Consent to Participate in the Vehicle Assist and Automation Pilot Program

Introduction

The Vehicle Assist and Automation Pilot Program is being conducted by the California PATH (Partners for Advanced Transit and Highways) Research Program at the University of California, Berkeley. We appreciate your willingness to learn about and potentially participate in this study. This research project is being conducted under the direction of Professor Alex Skabardonis, Director of California PATH, and Wei-Bin Zhang, Transit Program Leader at California PATH. It is sponsored by Caltrans in partnership with the U.S. Department of Transportation's Federal Transit Administration (FTA) and in partnership with several transit agencies, including your own. FTA has also independently contracted with the University of South Florida's Center for Urban Transportation Research to serves as an independent evaluator and reviewer of this research project.

Purpose

The Vehicle Assist and Automation (VAA) project demonstrates the technical feasibility of transit bus automated lane-keeping and automated docking systems and how these systems can improve transit agency operational efficiency, performance, and service quality. In this research study, we are outfitting several transit buses with VAA capabilities at specific locations along their routes. When a VAA-equipped bus is traveling over a VAA-equipped location, the VAA system can be activated to provide assistance in steering the vehicle and maintaining lane position. We will be collecting data on how drivers use the VAA system and if the system's usage has an impact on overall operations.

Procedures

If you decide to participate in this study, it will consist of three parts. First, there will be a driver training session at which an instructor will show you how to use the VAA system, and you will get a chance to become familiar with driving with the VAA system. The driver training session should take less than one day and will include both training on the VAA test track that has been set up in your transit agency's bus yard and training on non-revenue runs along the actual bus routes that have been VAA-equipped. The training session will include the following:

- A brief explanation of how the system works.
- An inspection of the bus showing where all VAA equipment is installed.
- An explanation of the driver interface (displays and controls) and possible failures that could be encountered (and what to do about them)
- A demonstration drive, with the instructor doing the driving.
- As many test track runs and non-revenue runs with you driving the bus and with an instructor present as necessary until you feel comfortable with the system.

In the second part of the study, your transit agency will schedule you on revenue-generating runs using a VAA-equipped bus on a VAA-equipped route, but your agency will ask that you do not use the VAA system for a period of several weeks or several months, depending upon the particular agency. During this period, the VAA system will be recording data even though it is not being activated to allow us to compare driving without the system to driving with the system.

In the third part of the study, your transit agency will again schedule you on revenue-generating runs using a VAA-equipped bus on a VAA-equipped route, and you will be able to use the VAA system whenever it is available to be activated. The study will last for approximately six months or until you are transferred off the VAA-equipped routes. The VAA system will be recording data even when it has not been activated.

It is important to remember that the VAA technologies being studied in this project do not replace you as the driver. These systems are designed to supplement your capabilities on certain segments of the roadway, helping to guide the steering when going through narrow lanes or when performing precision maneuvers such as docking. There are no sensors in the system to detect or react to obstacles in the roadway. You as the driver will always remain in full control of the vehicle speed and braking, and you will always have the ability to override the VAA system by turning it off or by applying a little bit of force to the steering wheel.

During the project, we will be collecting data such as time, speed, steering, GPS, magnetic guidance parameters (when traveling on a stretch of road that is outfitted for the VAA system), and VAA system usage. However, it is important to note that the information being collected in this project does not include video or data from any sensors that might be able to tell anything about the situation. Thus, even though the data would be able to tell us that a driver swerved or hit the brakes, we will not be able to know why a driver took a particular action.

Benefits

There is no direct benefit to you from the research. We hope that the research will eventually benefit the efficiency of transit operations.

Risks

This study presents minimal risk to you. However, since the study involves driving a bus, there is always the potential for a crash, either related to or unrelated to the VAA system operation and use. Training on the use of the VAA system will be provided to you, and you will not be asked to carry passengers while using the system until you feel comfortable doing so. Additionally, as with all research, there is a chance that confidentiality could be compromised, but we are taking precautions to minimize this risk.

Confidentiality

All of the information that we obtain from or about you during the research will be kept confidential. We will not use your name or identifying information in any reports resulting from this research. We will protect your identity and the information that we collect from you to the full extent of the law; however, this does not include subpoena. Should you be involved in a crash while driving a VAA-equipped bus, the data collected may be subpoenaed as evidence.

This project includes collaboration with an independent evaluator, and we will be providing the independent evaluator with a subset of the data collected during this study. However, we will be providing the independent evaluator with de-identified data only. The independent evaluator will have no way to match the data provided to a specific driver. Furthermore, after this project is completed, we may make the data collected during your participation available to future researchers for use in future research projects. If so, we will continue to take the same precautions to protect your confidentiality and preserve your identity from disclosure.

Costs and Compensation for Study Participation

There are no costs and there is no compensation for participating in this study. Participation in this study will take place during your normal working day while you are working for your transit agency. This study will not ask you to spend time outside of your working hours.

Treatment and Compensation for Injury

If you are injured as a result of taking part in this study, care will be available to you as it normally would be if you were injured on the job while driving a bus or route that was not equipped with the VAA system.

Rights

Your participation in this research is voluntary. You are free to refuse to take part, and you may stop taking part at any time. Attached to this consent form is a letter from your transit agency confirming that you are free to decline to take part in and/or you may stop taking part in this research at any time, without penalty or loss of benefits to which you are otherwise entitled.

If you have any questions about the research, please talk to your supervisor, who can relay questions to us, or you may directly contact the project leader, Wei-Bin Zhang, at California PATH, (510) 665-3552. You will be given a copy of this consent form for you records.

If you have any questions or concerns about your rights or treatment as a research subject, please contact the office of UC Berkeley's Committee for the Protection of Human Subjects, (510) 642-7461 or subjects@berkeley.edu.

I have read and understood this consent form, and I agree to take part in the research.

(Signatures of participant and observing researcher)

U.S. Department of Transportation
Federal Transit Administration

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https://www.transit.dot.gov/about/research-innovation