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LIST OF 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 Transit 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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Bob's Machine Shop helped design the steering actuator. They applied their impeccable judgment and technical expertise to all matters from design to minute details of packaging.

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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, while 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 in order to deliver 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 spear-headed efforts in developing and demonstrating VAA systems as well as in assessing their impacts on bus-based transit systems. The 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 following four phases: design, development, deployment, and operations. In the design phase, the system architecture and requirements were finalized, detailed specifications for components and interfaces were developed, 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 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

[1] The LTD deployment tested the magnetic marker sensing technology only. The AC Transit deployment was going 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.

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, revenue operations, as well as final documentation.

The VAA system design phase started with the development of the system requirements and interface requirements. The VAA 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; they 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; they 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 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, where 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 all components functions according to the technical specifications and 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 Richmond Field Station). 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. Over 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 U.S. 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, as well as 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 and the instructors' feedback were incorporated into the training procedure and material. After the procedure and material were delivered the instructors, the instructors 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 one and a half months for further validation of the system performance and reliability. Subsequently, a LTD media event occurred 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 dataset and subject dataset were collected. The objective dataset include quantitative performance data and transit property record keeping, while the subjective data set included perceived performance and reliability of the driver and the passengers.

The quantitative system performance data was recorded by the onboard data acquisition system. To evaluate and identify the performance of the VAA system, this data was analyzed to investigate tracking accuracy, ride quality/smoothness, system robustness, system availability, safety-related observations, fault management events, driver's response to events, as well as 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 has a standard deviation less than half of that achieved by the manual steering. The monthly standard deviations of the lane keeping lateral deviation are between 6.07 cm and 7.68 cm for automated steering, while the monthly standard deviations of the lane keeping lateral deviation are between 14.79 cm and 16.84 cm for manual steering. For the precision docking, the standard deviations of the docking errors at the six stations for the manual steering range from 4.18 cm to 7.15 cm, while the standard deviations of the docking errors at the same six stations under automated steering range from 0.73 cm to 1.02 cm. (It turned out that 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 indicates no noticeable impact of the automated steering on the 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 warmed the operator accordingly. The revenue service and those incidences demonstrate that the VAA system itself has been reliable and the system fault detection and management functioned correctly. Regarding false alarms, the VAA system generated about one false alarm per month on average. 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.

Finally, this VAA project was one of the first vehicle automation projects that dealt with many real-world deployment issues. Those issues included: (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 a 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 of the magnets needed to be reinstallation 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 does exhibit a somewhat different "steering characteristics" that the operator learns to adopt.

- The VAA system maintains a consistent docking performance, and initial comments from the operators suggest the VAA system does reduce operators' 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 the 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 resulted from several maintenance problems, and 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 a system in the U.S.). Because of these delays, the project has only accomplished 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 State Route 92 due to the unresolved contractual issues between the University 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 a 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.

1.0 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 where congestion is severe and the potential for significant mode shift could be realized with high quality transit service.

Among the transit options, BRT is seen as a cost-effective alternative to more conventional fixed guide-way systems that are becoming increasingly expensive to construct and operate. As current funding (federal, state and local) for conventional fixed guide-way transit is becoming more limited, transit agencies have to come up with more cost effective alternate modes. In the recent development of BRT systems, where 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, while 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 rights of way. The narrow right of way 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 whether a dedicated bus lane can be provided.

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, while 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 should in large part be applicable to the more advanced VAA systems as well.

Stakeholders have shown significant interest in VAA. For the transit agency, 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 guide-way systems with the same, if not more, benefits. From the driver's perspective, the VAA system can be a means to decrease the workload and stress and, at the same time, allowing him/her to operate 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.

1.1 VAA Project Scope

To address the needs of the transit industry, the USDOT, through the FTA and the 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 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. The 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, Federal Transit Administration and USDOT ITS Joint Program Office initiated the VAA demonstration project. The California-Oregon team including AC Transit, and Lane Transit Agency, California Department of Transportation, California PATH Program at University of California at Berkeley was 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 land keeping) on an 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) DGPS with 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 State Route 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, with a largely dedicated right-of-way. It has eight intermediate stations as well as 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 State Route 92 due to unforeseen project delays and the 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 initially completed 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 components' design, fabrication, and initial testing. The main hardware components included the steering actuator, magnetic sensor bars, DGPS/INS units, controller computers, the 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, 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. University of California at Riverside was responsible for the development of GPS/inertial measurement unit integration. IMI is responsible for the initial decision on which control computer. In Phase 2, the first sets of hardware components as well as baseline software modules.. 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 platform 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. The magnet installation 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 require repeated testing include precision docking, lane guidance, driver training, failure detection and emergency driver warning and reactions were therefore done on the LTD yard track. After subsystem and system level testing were carried out on the RFS and LTD yard test tracks, testing then commenced at the public operational testing site.

It is worthwhile noting that many operational situations and environments can only occur on the public roads, and thus can only be tested in the real world conditions. Since safety is the most important consideration while testing on the public road, the system safety management functions needed to be in place before any closed-loop control could take place on such roads. The basic safety management functions included fault detections and management, as well as the redundant operations. Strict testing protocols and safety procedures were found to be critical to prevent software operational errors and thus were also 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 as well as validating the reliabilities based on the testing on the EmX track. The automatic steering control testing was started on July 2012 and the lane-keeping and precision docking performances were 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 operations by LTD in April 2013. Parallel to completing the above tasks on the LTD test bus, the VAA components were installed onto two AC Transit test buses in October 2011. The system integration and verification tests were also 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, as well as 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) of the Center for Urban Transportation Research (CUTR), a part of the University of South Florida. 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 on June 10, 2013. VAA revenue service operations were suspended between October 15, 2013 and October 10, 2014 due to the contractual and liability issues. VAA revenue service operations started again on October 11, 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 State Route (SR) 92.

As it is not practical at the proposal stage to anticipate many real-world issues including 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 and the team did its best to minimize the 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 the contract and liability issues between the University of California and Caltrans, as mentioned above, three months of accumulative unavailability of the buses from several maintenance problems, and 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 a system in the U.S.).

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 United Stated.

1.2 VAA System Overview

This section provides the definition of major VAA system components and applications as well as the 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.

1.2.1 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 utilized in Bus Rapid Transit applications such as lane guidance, precision docking, lane keeping, or lane changing as described below:

a) 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.

b) 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 where visibility is poor or limited. Exemplar applications are wide vehicles traveling on narrow roadways and bridges, or through narrow toll booth lanes.

c) Lane keeping or lane change: Driving vehicles on the selected lanes or making transitions between lanes
Lane keeping or lane change 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.

d) Longitudinal control: Accelerating or braking
The use of speed control is optional for VAA functions, for example, the VAA system developed in this VAA 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. Take the example of precision docking; with the longitudinal control, the bus's speed can be controlled so that the bus will not only approach the station with smooth speed profile, but also stop at a pre-designated location of the docking station to facilitate passenger boarding and alighting.

1.2.2 VAA System Functional Blocks

The VAA system can be partitioned into several functional blocks. Figure 1-1 shows the 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 can also 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, and door opening, etc. It provides necessary information for controller and fault detection/management.
    - **Vehicle position sensing**: Through the interaction with sensor reference infrastructure, vehicle position sensing detects the vehicle position with respect to the lane center. It is the key sensor in the VAA-PD and 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.

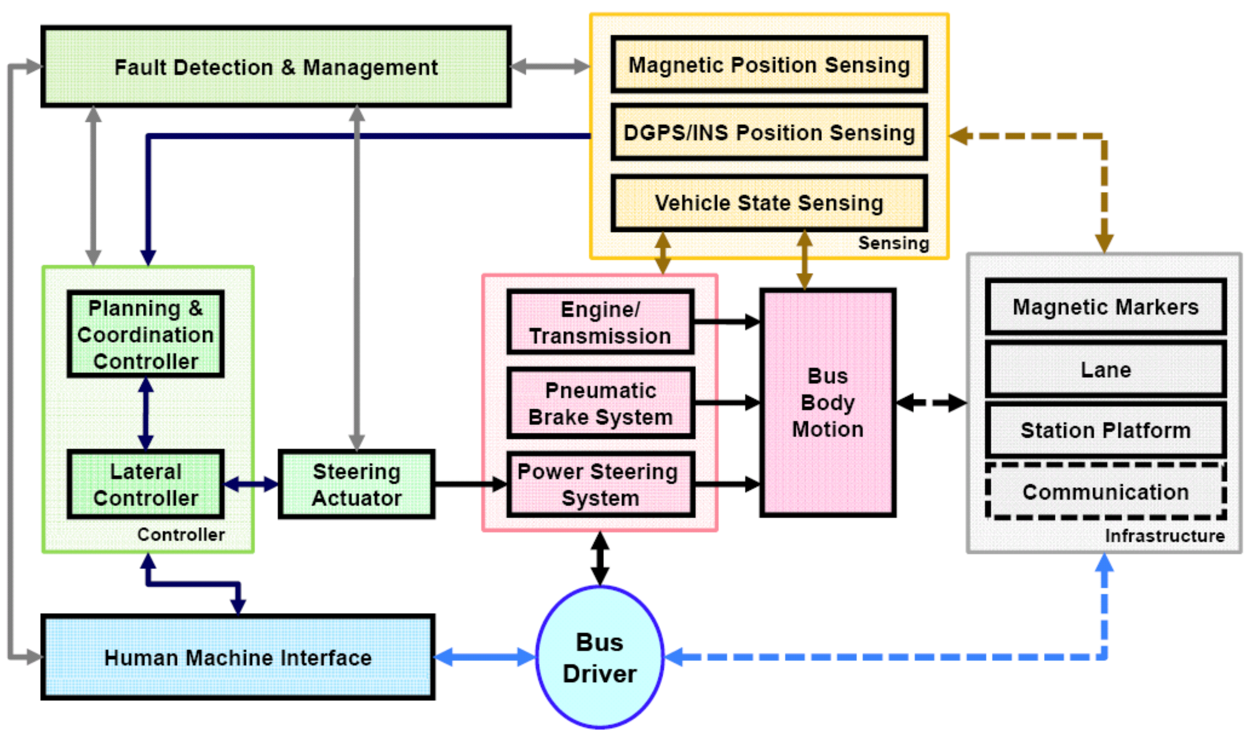

Figure 1-1 Functional Block Diagram of the VAA System

[2] The LTD deployment tested the magnetic marker sensing technology only. The AC Transit deployment was going 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.

- ***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 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) .

- ***Human machine interface (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, system activation or deactivation via multiple modalities (audible, visual, or haptic feedback to driver).

- ***Fault detection and management***: Fault detection and management form a necessary functional block for the VAA system because it is a safety critical system. Alerts will be 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 such 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. Lane keeping and docking function is maintained, if such degraded operations are possible, before derivers' taking over.

1.3 VAA Testing

Figure 1-1 provides an overview of the testing involved in the VAA project. Divided into four hierarchical levels, the VAA testing includes: 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.

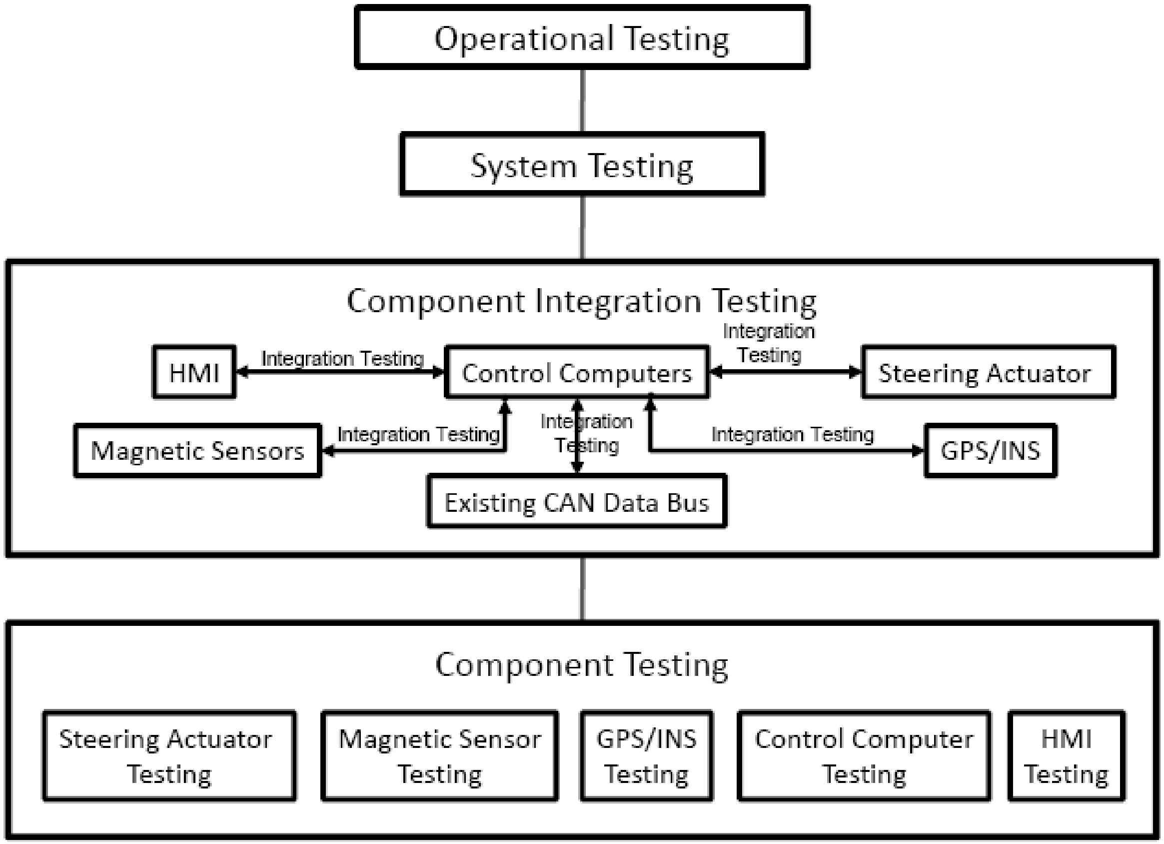

Figure 1-2 Overview of Testing involved in the VAA Project

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 (Chapter 2). Component testing was conducted jointly by the VAA system engineers at PATH and the component developers.

The component integration testing followed the 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 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 components' reliability and robustness. Finally, the 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 VAA 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 of 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, as well as the independent evaluator; based on these discussions, the system operation procedures and the operational test plan (including the data collection and analysis procedures) was 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, relatively small amount of bugs were 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, Oregon. Field operational testing for AC Transit in California was not carried out due to contractual issues. Quantitative measures, including lateral sensing and control accuracy, ride quality measures, were collected using on-board data recording module. Qualitative measures were obtained through interviews with operators, drivers, and passengers; these measures included impressions of ease of use of the VAA system, the HMI design, operator and passenger comfort in automated operation and during transitions, and other general impressions and comments.

1.4 Report Organization

The remaining report is organized as follows:

Chapter 2.0 Requirements reports the requirements for the VAA system. The requirements include the general requirements for electronic guidance systems, the detailed VAA system requirements, the on-board interface requirements, and the infrastructure-vehicle interface requirements. The general requirements serve as a guideline for the system design and the system and interface requirements development. The VAA system requirements include safety and performance requirements for each VAA function, and the technical specifications for each subsystem. The VAA interface requirements describe the mechanical interface, power supply, and data communication for the key subsystems. The requirements on the interfaces between the vehicles and the infrastructure focus on the infrastructure-based reference support for accurate determination of vehicle position with respect to lane center.

Chapter 3 Development of Prototype VAA System describes the key components, software modules, software architecture, and 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, while 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.

Chapter 4 Component and Integration Testing discusses the lower levels of testing. The component tests ensure 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.

Chapter 5 Field Testing discusses the higher levels of testing. The chapter first provides an overview of the test facilities at LTD and AC Transit. It 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 the VAA system is working correctly and consistently before the field operational tests can begin. Revenue service results provides 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.

Chapter 6 Lessons Learned and Recommendations presents the lessons learned from the project and provides recommendations.

2.0 Requirements

The 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 the 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 the infrastructure, the interface specifications also define interfaces between the vehicles and infrastructure in order 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, and 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 requirements and interface requirements were adopted and improved to guide the development of the prototype VAA system for field operational testing.

2.1 General Considerations for VAA System Requirements

The 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

2.1.1 Safety

Although VAA systems can potentially 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. It is therefore critical to understand the nature and potential consequences of these failures or faults, to design the system to meet some important safety criteria and, from a risk management perspective, to manage the risk involving the introduction of new technologies.

A. **Failures, faults and their potential consequences:** Failure and faults can occur at any point in the VAA system. A number of hazardous consequences can develop due to system failures/faults, including but not limited to: 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 he is not given advance warning of this failure/fault and does not have adequate time to properly take over control, and 3) driver mistakenly takes over and causes the vehicle to deviate from the desired path.

B. **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 either the capability of compensating automatically and safely for a failure or the capability of 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 to take control and either bring the bus to a stop or continue manual operation.

A critical part of this handover is insuring 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 touch 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.

2.1.2 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 the 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 DOT relax this requirement for VAA equipped buses.

The second performance requirement for VAA systems 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 ADA-specified requirements for docking of light rail systems (maximum three inches horizontal and 5/8 inch vertical distance) which would also apply to VAA-PD equipped buses and all other buses that satisfy the ADA requirements. Previous discussions have yielded a general consensus that a maximum two inches 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.

2.1.3 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. While 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 utilizing 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 the 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], while GPS is more subject to satellite blockage and signal interference.

2.1.4 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 each bus' tracking system could be checked as the bus left the yard to begin its daily run.

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[3] In order 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 will be relatively easy to detect.

Design again 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 that the bus can quickly be placed back in service. 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 in order to maintain the desired level of service.

Infrastructure availability should also be taken into consideration. Will local weather conditions have an adverse effect, e.g., snow or ice on the guide-way? 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 on-board or with the infrastructure, that cannot be repaired, the system should be designed so that the bus can operate manually, albeit at reduced speed.

2.1.5 Maintenance

The VAA system should be at least as durable as other onboard systems so that 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 replacement of a module that is beyond repair will be cheaper, pulling 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).

At the present time the service life of a bus is approximately 12 years. Given the current pace of changing technology, is it a reasonable expectation that the 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? While the overall guidance system may be state-of-the-art, it should be constructed with proven, off the shelf components that can reasonably be expected to be around for a long time or sufficiently module that can be replaced with relative ease. Also, there should be assurance that future upgrades will be functionally backwards compatible so that the entire system will not have to be replaced.

2.1.6 Infrastructure Requirements and Modifications

The required modifications of infrastructure to adopt VAA systems depend on the type of operational venues, 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: This will require the construction of added lanes and dividers to utilize the median as dedicated bus lanes.

- New division of existing roadways into special bus lanes: This may involve the re-striping of existing lanes into narrower paths or the creation of a shoulder lane.
    - Narrow bridge or toll booth: This 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 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, thus truly passenger-friendly, expedient alighting and boarding can be realized.
- Technology Selection
    - Vision-based guidance: This approach 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: This involves the installation of magnets in the pavement, typically at intervals of 1 meter or more.
    - GPS based guidance: Although this approach does not require direct infrastructure modifications to the roadway, differential stations and communication means may need to be set up to provide the appropriate differential information to the GPS receivers in order to obtain the desired accuracies.

2.2 VAA System Requirements

Based on the general considerations for system requirements and the VAA system functional block diagram described in Section 1.2, the 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 that it will not imperil or degrade 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).

The 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].

2.2.1 Safety Requirements

Since it is impossible to design a VAA system to be free of faults and failures, it is critical that 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). Accordingly, the safety requirements include three dimensions: redundancy in system hardware, fault detection capability, and fault management capability.

2.2.1.1 Hardware Redundancy

It is essential that a production 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:

(1) Redundancy in vehicle position sensing
The VAA system (as described in Section 1.2) 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 the 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 (i.e., front magnetometers and rear magnetometers) 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.

(2) 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.

[4] The reliability and availability requirements, as described in the general requirements in Section 2.2, have been implicitly included in the safety and performance requirements; therefore, they are not listed as separate subsections.

(3) Redundancy in control computers
Two control computers are included for redundancy purposes.

(4) Redundancy in HMI subsystems
Two HMI subsystems are used for redundancy purposes. Warning shall be provided as long as one of the two 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.

2.2.1.2 Fault Detection

2.2.1.2.1. Local detection of faults in subsystems

(1) 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.

(2) 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.

(3) 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.

(4) 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.

2.2.1.2.2. Fault detection in the VAA system

(1) 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 heart beat for health monitoring, and the commands and outputs from each control computers shall be compared to detect any inconsistency.

(2) 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.

2.2.1.3 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 the 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 where the VAA can no longer perform its desired functions or the performance degradation is unacceptable, driver's 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.

2.2.2 Performance Requirements

This section specifies the performance requirements for the following VAA functions: 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 in Section 2.2.3.

2.2.2.1 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.

2.2.2.1.1. Docking accuracy

The performance of precision docking is subject to legal performance requirements from the ADA. The complete review can be found in **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). 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 while 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.

2.2.2.1.2. Operating conditions

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

2.2.2.1.3. Transition Characteristics

(1) 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.

(2) Transition time
The transition from manual to auto modes shall take no greater 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 greater than 0.15 seconds after the driver initiates a transition command.

2.2.2.2 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.

2.2.2.2.1. 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. a 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 to 60 percent of the maximum allowable deviation (0.375 ft to 0.45 ft) for the whole speed operating range. It is worthwhile noticing 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 nonholonomic 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.

2.2.2.2.2. Operating conditions

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

2.2.2.2.3. Transition characteristics

(1) 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 guide-way.

(2) Transition time
The transition from manual to auto modes shall take no greater 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 greater than 0.15 seconds.

2.2.2.3 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].

2.2.2.4 HMI and Driver Interaction

The system shall provide feedback that a request has been received from a driver so that the driver 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, the system shall provide some preview information to the driver, such as through sounding a tone.

2.2.3 Technical Specifications of Subsystems

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

2.2.3.1 Vehicle Position Sensing Capability

How to 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.

2.2.3.1.1. 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 feet from the bus center was required.

2.2.3.1.2. 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.

2.2.3.1.3. 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 clear view of the sky and urban environments with partially or totally blocked sky, and clear view of road or foggy weather with low visibility.

2.2.3.1.4. Timing and update rate

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

(1) 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 that 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 and 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 s to allow accurate tracking of bus dynamics at the 10 Hz update rate.

(2) Update Rate
The requirement is similar to the time delay requirement. The update rate shall be at least 5 times and 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 sub-system shall support a data update sufficient enough to ensure no magnet update data are missing.

(3) 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.

2.2.3.2 Subject Vehicle Status Sensing Capability

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

2.2.3.2.1. Vehicle status parameters

(1) 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.

(2) Yaw rate

The maximum yaw rate that the sensor can measure shall be at least 150 deg/sec while 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.

(3) 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.

(4) Data Bus communication
Since an on-board J-bus or data network has become a primary trend for transit vehicles, the VAA systems shall be equipped with capabilities to read and send (if required) data from the J-bus.

(5) 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.

2.2.3.2.2. Events

Events relevant to VAA applications, such as door open/close, light on/off, etc., which indicate conditions that are important to VAA applications, 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.

2.2.3.3 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.

2.2.3.3.1. Steering Actuator Functions

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

(1) 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.

(2) 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.

(3) 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.

(4) 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.

(5) 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.

(6) 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.

(7) 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.

2.2.3.3.2. 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 which 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 that 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 degree/second at the tire or 540 degrees/second 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 greater than 0.5-1 seconds, and the transition from automatic to manual takes no greater 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 & 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.

2.2.3.4 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.

2.2.3.4.1. Interface Contents

(1) 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.

(2) 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.

2.2.3.4.2. Processing capability

(1) 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.

(2) 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 Hz to 20 Hz.

2.2.3.4.3. 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.

2.2.3.5 Control Computer

2.2.3.5.1. 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.

2.2.4 Maintenance Interval Minimum Requirements

(1) The mileage interval between maintenance for the VAA system shall not exceed 6000 miles.
(2) The time interval between maintenance for the VAA system shall not exceed one month.
(3) Routine diagnostics, including daily, weekly and monthly test procedures, shall be provided.

2.2.5 Infrastructure Requirements

2.2.5.1 Roadway sensing and construction

(1) 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.

(2) Roadway and transit stop construction

The 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, the vehicle type (e.g., articulated or non-articulated buses), as well as the 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

[5] Enclosures constructed for either indoor or outdoor use to provide a degree of protection to personnel against incidental contact with the enclosed equipment; to provide 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.

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 cm to 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.

(3) Digital Map

2.2.6 Driver Qualification and Training Requirements

2.2.6.1 Driver Qualification

(1) Transit vehicle experience

The drivers of the VAA-equipped buses shall have at least (one) year of transit vehicle driving experience based on transit agency's qualification requirements as well as the operational complexity of the deployed VAA system.

(2) Training and evaluation tests

The drivers of the VAA-equipped buses shall take both initial and follow-up training courses and pass evaluation tests in order to operate the VAA-equipped buses.

2.2.6.2 Training

(1) System training

The system training shall cover issues related to the overall VAA application, system operation, and fault management.

(2) HMI training

The HMI training shall familiar the drivers with system responses driver interaction, and emergency handling actions.

2.3 VAA Interface Requirements

The objective of the interface requirements is twofold. First, the interface requirements are to ensure that the VAA system can interface seamlessly with the types of transit buses chosen for the VAA applications. Second, the interface requirements should 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.

The transit vehicles are mostly manufactured based on individual transit agencies' customized operational requirements. Although certain requirements are established industry-wide, most of the system or subsystem requirements of the transit vehicles are also driven 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, the understanding of how the VAA system would interface with the existing bus systems and components of these two types of transit vehicles was 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, while 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.

<u>The fully integrated approach</u>

- The integrated approach enables the physical design and the performance of the basic bus driving functions to better meet the VAA needs.
- However, the cost of the integrated approach is extremely high and it is very difficult to adapt such VAA technologies to existing buses.
- Additionally, problems can occur if the VAA functions are too closely coupled with the 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 will unlikely require standard interfaces for VAA components and newly designed buses.

<u>The add-on approach</u>

- The add-on approach, though less integrated than the 'integrated approach', supports standalone components to fit onto existing buses and therefore could likely have wider applications.
- From the interface perspective, it is very important to have standard interfaces when VAA components and systems are 'add-ons' to existing buses.
- The interfaces would largely rely on existing bus designs and only specify necessary modifications of the existing systems in order to allow compatibility between the add-on components and the existing buses and infrastructure.

The prototype VAA system adopts the add-on design approach and is 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 sub-systems of the transit buses that were used in this VAA project (as described in Section 1.2.3). 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 the system level requirements, the VAA interface requirements can impact or be impacted by the 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, the VAA interface requirements need to be consistent and compatible with the VAA system design and to 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 are also built upon 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, it is the PATH team’s goal 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 is employed (i.e., the design is carried out for each VAA system functional block in each category). The emphasis is placed on important functional blocks such as vehicle and lane position sensing and steering actuation.

Three types of communication protocols are commonly used in the 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.

2.3.1 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: the vehicle J1939 CAN bus (via a CAN bus gateway if necessary), the sensing unit including vehicle positioning sensors, the steering actuator, and the HMI subsystems.

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:

- 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?

The answers support the definition of the message framework as well as information interface requirements.

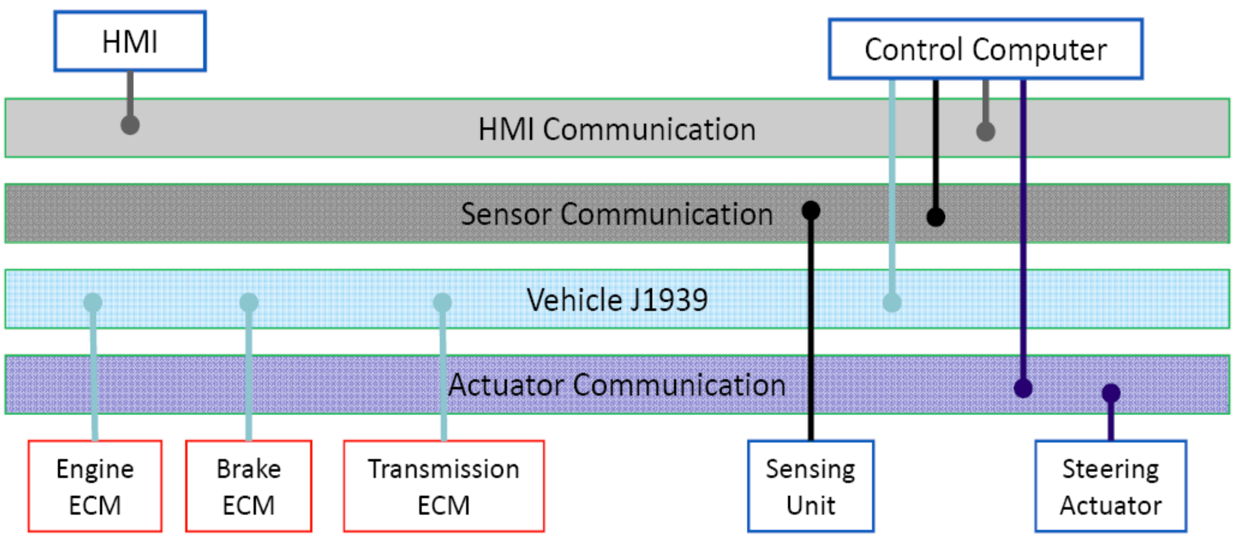

Figure 2-1 Schematic for VAA communication network[6]

Different communication protocols have been evaluated for distributed real-time control systems, especially for the safety-critical automotive applications such as X-by-wire (X means 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.

<u>CAN communication protocol</u>

[6] ECM: Electronic Control Module

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 a CAN 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 CAN is an event-triggered communication protocol and requires careful analysis of the relative priorities and frequencies of all messages on the network in order 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), and 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 the 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.

2.3.1.1 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 ID 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 utilized 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.

2.3.1.2 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.

2.3.2 Vehicle and Lane Position Sensing

How to determine 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 magnetometer 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.

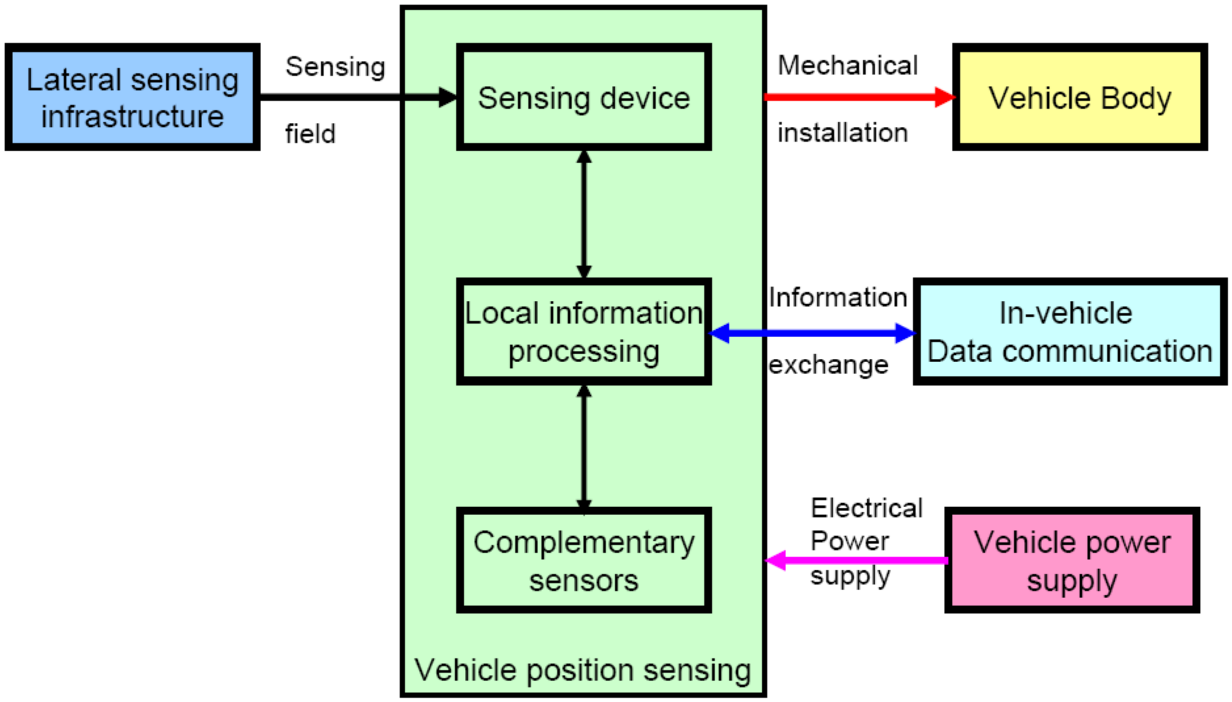

Figure 2-2 Schematic for Vehicle Position Sensing

2.3.2.1 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.

2.3.2.2 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 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.

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.

2.3.2.3 Interface Requirements - Data Communication from and to the 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.

2.3.2.3.1. 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.

2.3.2.3.2. 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.

2.3.2.3.3. 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.

2.3.2.3.4. 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 shall 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.

2.3.2.3.5. 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).

2.3.2.3.6. 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, while the messages from the DGPS/INS unit shall include a sensor type indicating it is GPS.

2.3.2.3.7. 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.

2.3.2.3.8. 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.

2.3.2.3.9. 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.

2.3.2.3.10. System Command

System commands, including reset, calibration and change system parameters, shall also be included in the messages.

2.3.3 Vehicle State Sensing

The VAA system implements vehicle state sensing in two ways. First, the VAA system 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).

2.3.3.1 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.

2.3.3.2 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 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.

2.3.3.3 Interface Requirements - Data Communication

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

2.3.3.3.1. 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.

2.3.3.3.2. Yaw rate

Yaw rate 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.

2.3.3.3.3. 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.

2.3.3.3.4. 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.

2.3.3.3.5. 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.

2.3.4 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.

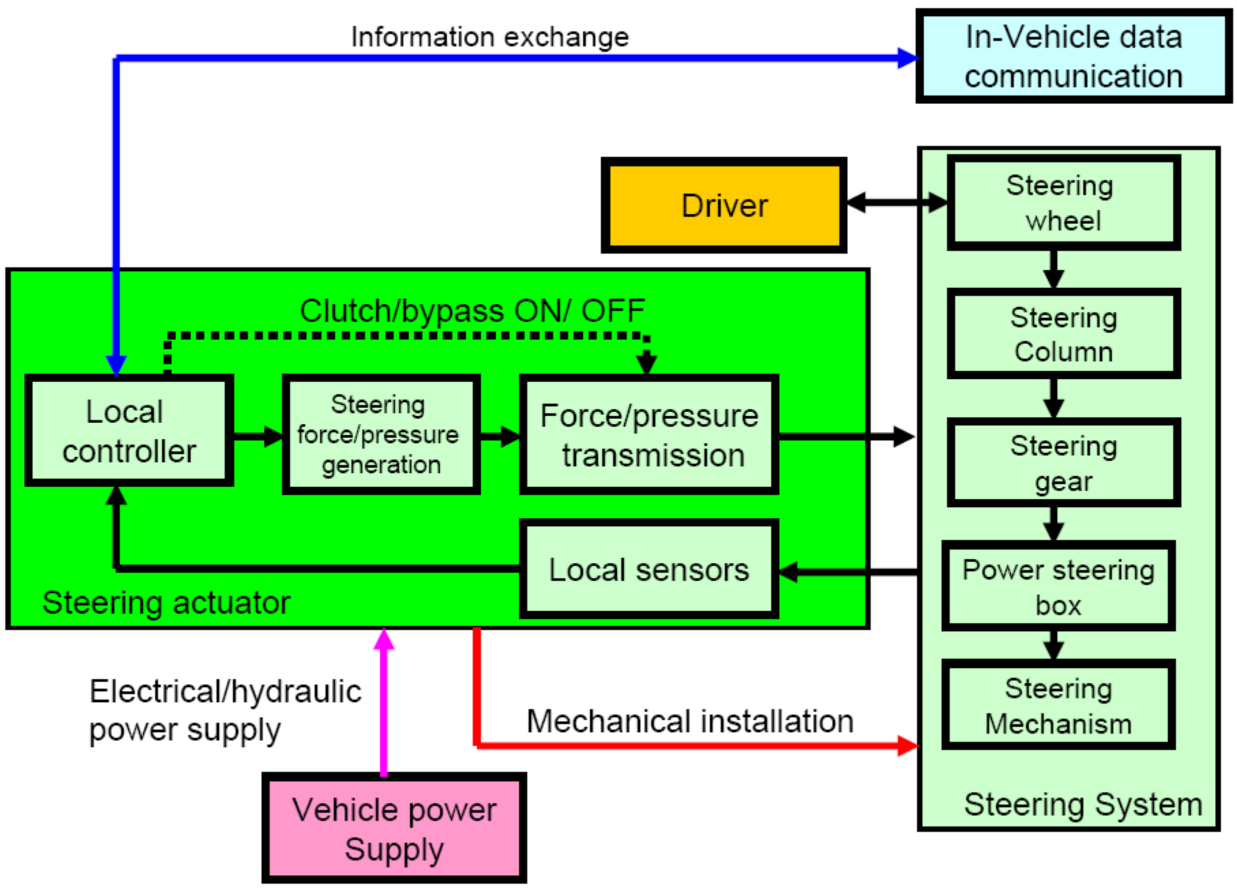

Figure 2-3 Schematic of the Steering Actuator

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.

2.3.4.1 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 shall 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.

2.3.4.2 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.

2.3.4.3 Interface Requirements - Data Communication

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

2.3.4.3.1. Actuator ID

Actuator ID shall give unique identification of the messages sent to/from the steering actuator.

2.3.4.3.2. 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.

2.3.4.3.3. 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.

2.3.4.3.4. 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.

2.3.4.3.5. Health signal

A health message could be a heart-beat signal or a message counter embedded in the messages sent by the steering actuator.

2.3.4.3.6. 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 degrees 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.

2.3.4.3.7. 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.

2.3.4.3.8. 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.

2.3.4.3.9. 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.

2.3.5 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.

2.3.5.1 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 while 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.

2.3.5.2 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.

2.3.5.3 Interface Requirements - Data Communication

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

2.3.5.3.1. HMI ID

HMI IDs shall give unique identification of the messages sent to/from the HMI Modules.

2.3.5.3.2. 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.

2.3.5.3.3. 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 to 5 seconds in advance) and emergency takeover.

2.3.5.3.4. 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.

2.3.5.3.5. 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 the driver's 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".

2.3.5.3.6. 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.

Noncritical faults of the system shall also be detectable and 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.

2.3.5.3.7. Health

Health messages could be heart-beat 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.

2.3.6 Control Computer

2.3.6.1 Interface Requirements - Mechanical Installation

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

2.3.6.2 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.

2.3.6.3 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.

2.4 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' in order 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: 1) new or modified infrastructure design to take full advantage of VAA functionalities and 2) infrastructure-based reference support for accurate and robust determination of vehicle position with respect to lane center.

2.4.1 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 feet 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: 1) the vehicle floor height and boarding platform floor height need to be equal and 2) 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 [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.

2.4.2 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 with INS..

2.4.2.1 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.

<u>Magnets</u>: 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 inch diameter and 1 inch height are recommended for each magnet sensing reference point. Thus, the total height is 4 inches.
- 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 inch diameter and 1 inch thickness is used for each magnet sensing reference point.
-

<u>Magnet Track</u>:

- 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 meters for the prototype VAA applications.
- Diameter: The diameter of each magnetic marker hole shall be slightly larger than that of the magnets (1.0625" for ceramic magnet).
- Depth: The depth of the magnetic markers holes is recommended to be at least 1/4 inch deeper than the magnet (4.25" 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 centimeter along station, and 1.5 cm otherwise.
- Longitudinal accuracy: The maximum longitudinal error shall be less than 20 centimeters. However, the recommended mean error is within 5 cm.
- Magnets shall be installed no closer than 2 feet 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 the 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.

2.4.2.2 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 the lateral guidance
The location of the base station shall 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 the 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 meter accuracy while the

base-station-based DGPS position is typically within 0.5-1 meter 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 meter. Under such applications, the GPS-based sensing systems are typically used as a supportive sensing system rather than a primary sensing system.

3.0 Development of Prototype VAA System

The development of VAA system is reported in this chapter. The current conditions of the two commercial transit buses were 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 chapter 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.

3.1 Existing Bus Systems

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

- The VAA lateral control system interacts with the existing bus steering system, including its power steering, in order 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 VAA system and existing vehicle subsystems, it is essential to gather information about the key components and sub-systems of the transit buses that were used in this VAA project. The sub-systems 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.

3.1.1 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 (as shown in 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 is 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' Coach Bus

Figure 3-2 MCI 50’ Coach Bus Steering Wheel and Column

<u>New Flyer 60-Ft Diesel</u>

A New Flyer 60-ft diesel articulated bus, shown in the 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 is 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’ Diesel Bus

Figure 3-4 New Flyer steering wheel and column (60' 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.

3.1.2 Power Steering System

Heavy duty vehicles, including buses, typically uses 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 needs 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 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 Power Steering System Test Results 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)

M

New Flyer 60-ft Diesel Bus	10.6	≥15
50-ft MCI coach	Between 10 and 12	<15

3.1.3 Existing CAN bus

The CAN is a serial communication protocol which 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. This 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 zero is dominant over a one and a node has lost the arbitration when it has written a one but reads a zero 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 90's, the Society of Automotive Engineers (SAE) Truck and Bus Control and Communications Sub-committee started the development of a CAN-based application profile for in-vehicle communication in heavy duty vehicles. In 1998, the 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. These messages 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

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

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).

3.1.4 Electrical Power System

The vehicle electrical power system supplies electrical power to all vehicle subsystems. It 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

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

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.

3.2 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, together with the corresponding software modules, is as follows.

3.2.1 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, PATH team designed a prototype steering actuator and determined the actuator motor and relevant sensors. The basic sub-components 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, as well as 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.

3.2.2 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.

3.2.3 DGPS/INS Module

Different GPS modules are used in the LTD application and the AC Transit application. The LTD bus that is 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, as well as the associated antennae, software, and custom enclosure with cables and connectors. A high-precision DGPS/INS module developed by University of California at Riverside is 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, the PATH staff, with the support of the Univ. of California at Riverside also set up a DGPS base station with 900MHz communication broadcast at the test site along Route 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, while 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.

3.2.4 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, as well as 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.

3.2.5 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 and 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 is 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.

3.2.6 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. The HMI module is developed with redundant audio and visual feedback to the driver, and it 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 the 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.

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 3-5and Figure 3-6: LED indicators, buzzers, switches/buttons, and the steering wheel.

Figure 3-5 Driver VAA Interface Components for the LTD New Flyer 60-ft Articulated Bus

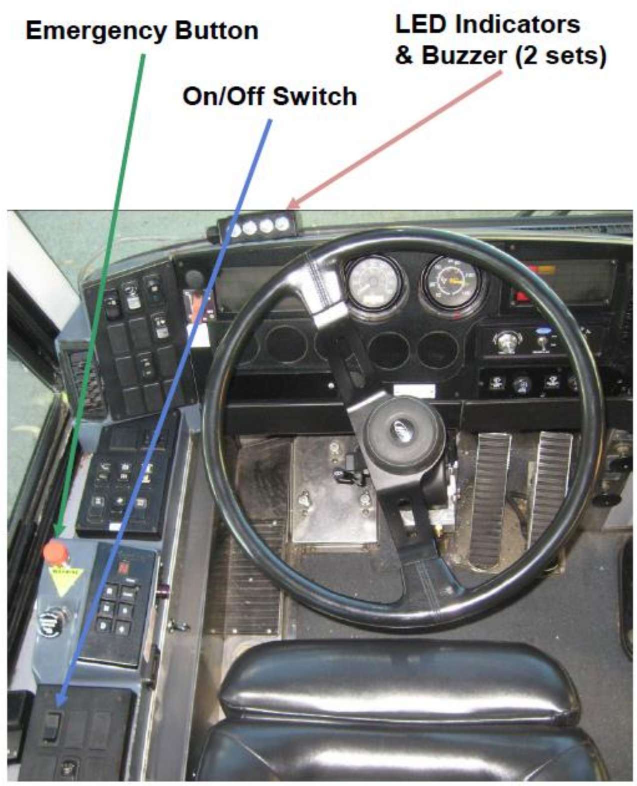

Figure 3-6 Driver VAA Interface Components for the AC Transit MCI Coach

3.2.6.1 LED indicators

As shown in Figure 3-5 and Figure 3-6, LEDs with four different colors were installed on top of the bus dashboard: amber, green, blue and red. 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: The 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: The 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: The 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: The 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.

3.2.6.2 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: A 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.

3.2.6.3 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.

3.2.6.4 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.

3.2.6.5 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.

3.3 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 with 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.

3.3.1 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[7] 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.

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.

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

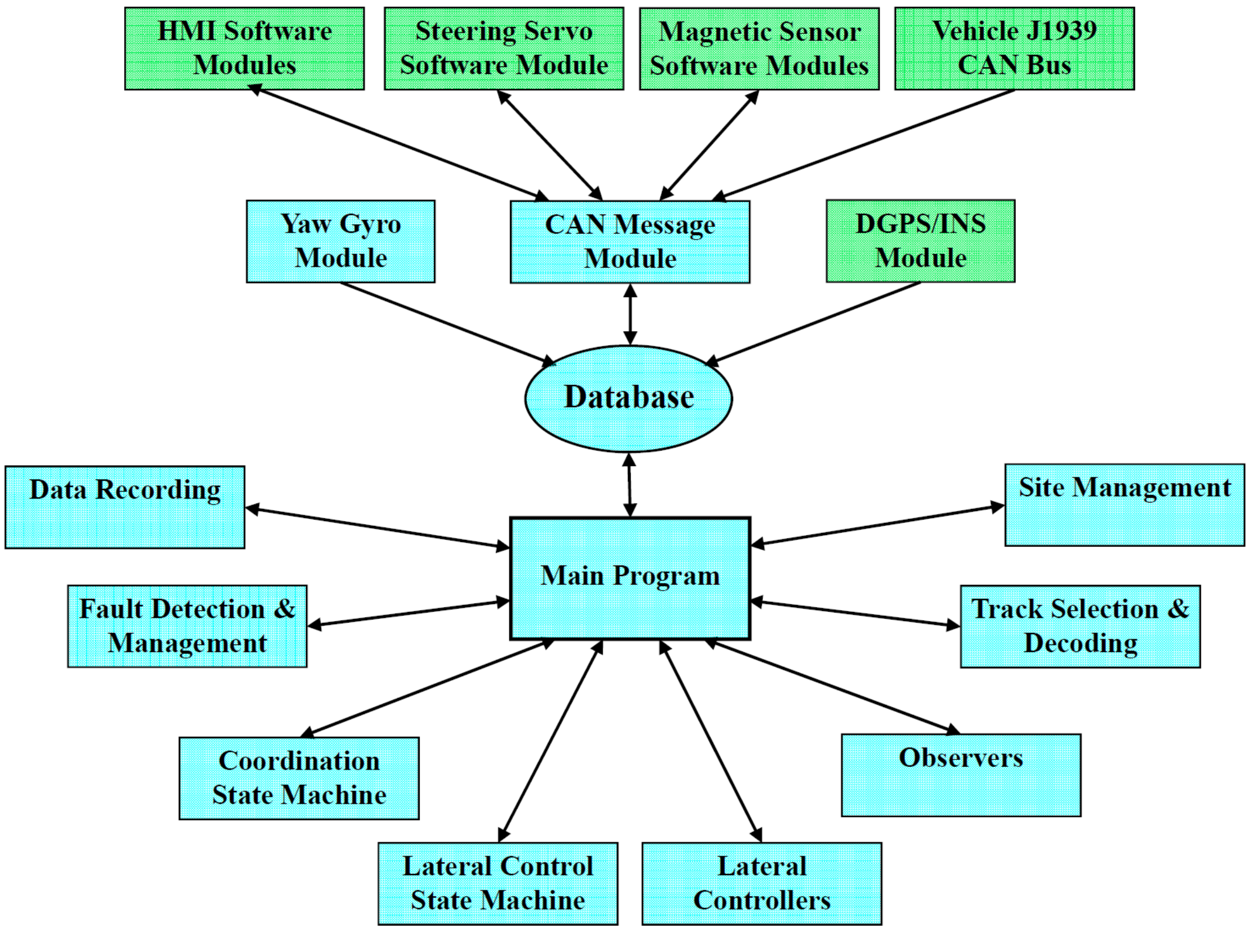

Figure 3-7 VAA System Software Architecture

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, OR, and the HOV lane on Highway 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 light-emitting diode (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.

3.3.2 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, as well as 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.

3.3.3 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.

3.3.4 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 in Section 3.1.3, 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 [7].

3.3.5 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).

3.4 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. **Error! Reference source not found.** 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.

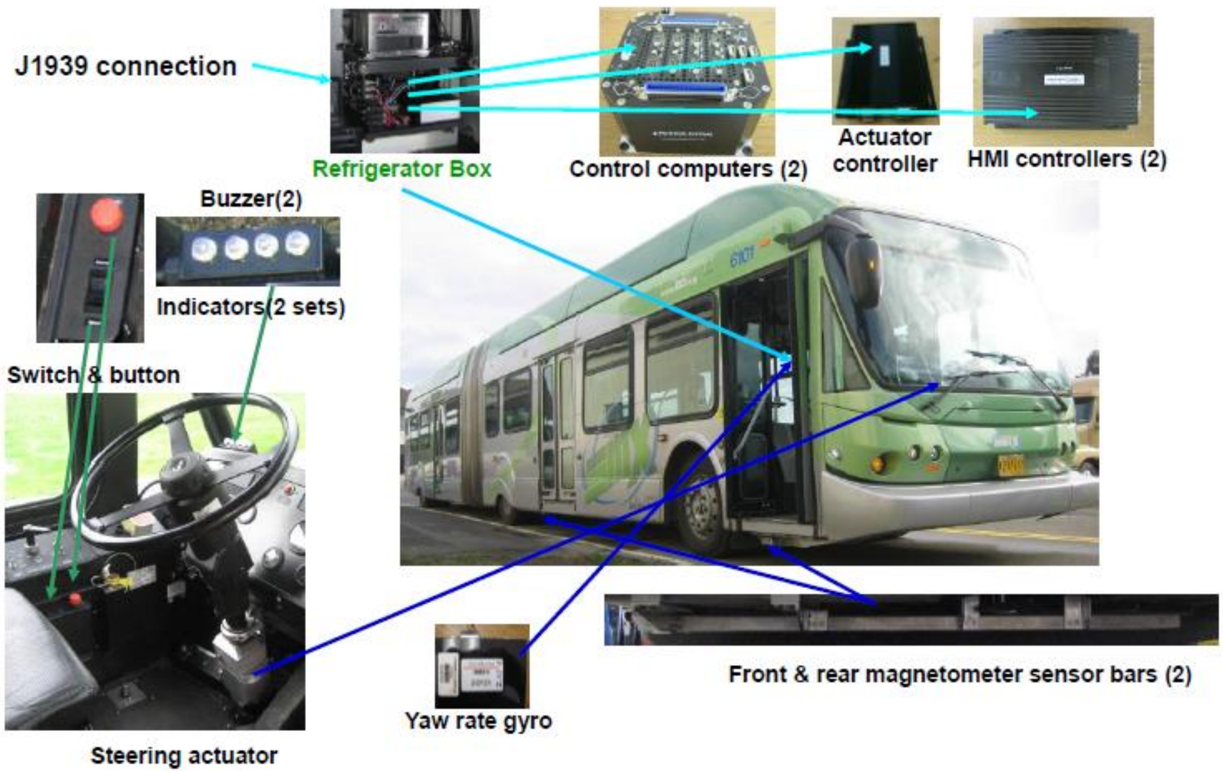

Figure 3-8 VAA system components and installation on the LTD 60-ft New Flyer bus

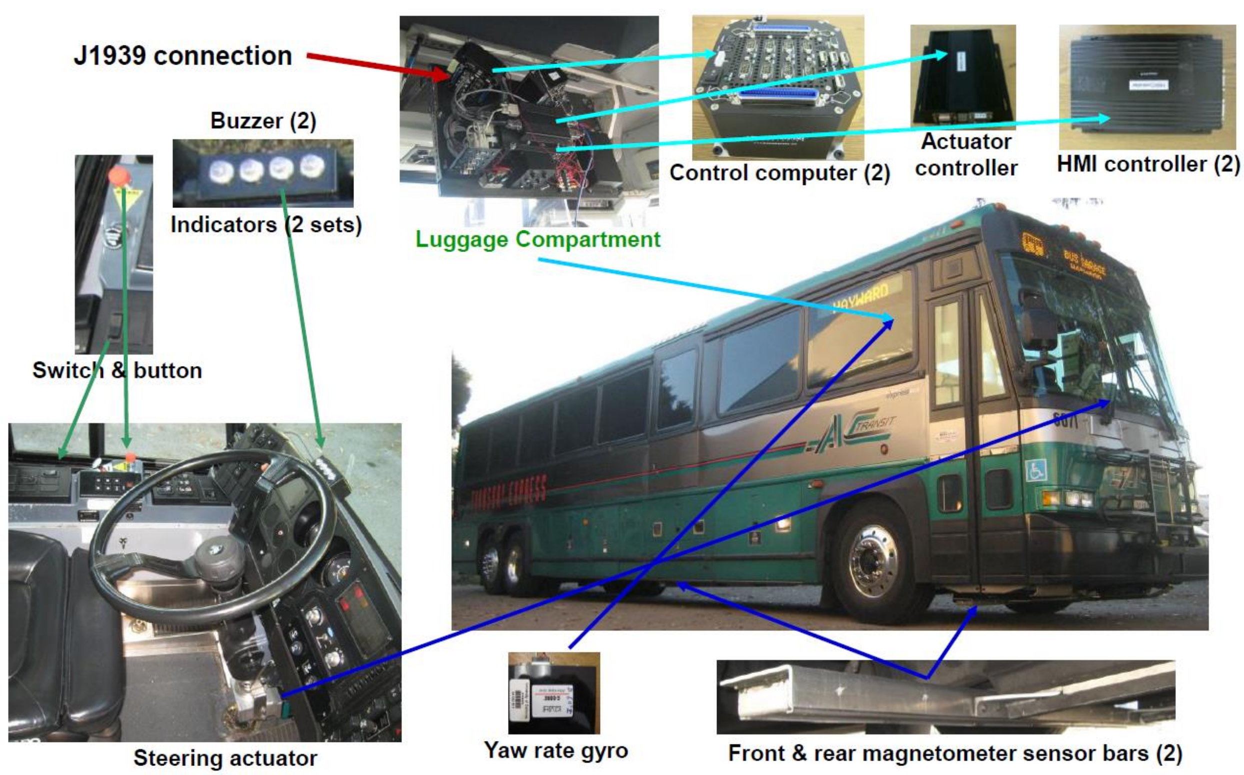

Figure 3-9 VAA system components and installation on the AC Transit 50-ft MCI Coach

4.0 Component and Integration Testing

As discussed in Section 1.3, VAA system validation included four hierarchical levels of testing: 1) component testing, 2) component integration testing, 3) system testing, and 4) operational testing. This chapter describes the component and integration tests, including the objectives, scope, resources and responsibility, assumptions for the component and integration testing, and testing methodologies.

4.1 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.

4.1.1 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, and so on
- 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 sub-system level; therefore, they 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 sub-systems as well.

4.1.2 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.

4.1.2.1 Basic test approach

The basic test approach employed by the component testing was “requirements testing” where 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.

4.1.2.2 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[8] 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; the component developers 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.

[8] The purpose of regression testing is 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].

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.

4.1.2.3 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 (Chapter 2) and the developers' SOWs.

4.1.2.4 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: 1) regression testing (bug regression) and 2) 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 that is 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, the project management, the system design and integration team, and the 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 won't be fixed. For example, a bug that was determined to be critical and had top priority falls 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.

4.1.2.5 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.

4.1.2.6 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.

4.1.3 Test Results

The key components of the VAA system -- steering actuator, magnetic sensor module, DGPS/INS module, control computer, and the HMI module -- were tested during the component testing. For each of the key components, features that need to be tested were determined based on the component specifications defined in the system and interface requirements. For each of these key components, 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.

4.2 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.

4.2.1 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 sub-systems:

- 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 sub-systems

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

4.2.2 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[9] 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

[9] 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.

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.

4.2.2.1 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/sub-systems 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/sub-systems 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.

4.2.2.2 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 sub-systems were aggregated into larger sub-systems to test the interactions among them. Eventually, all the sub-systems 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[10] 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.

4.2.2.3 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.

4.2.2.4 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 that is identified by the component integration test team is tagged as "problem/bug – needs fixing." All problems or bugs that have been resolved by the component developer or the PATH engineers are marked as "fixed – needs re-testing." When the corrected components and their interfaces pass through the regression testing, they are considered as "problem closed – bug fixed." If a problem fix fails a regression test, the test team would immediately notify 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 into the appropriate category and resolved each problem following the same anomaly resolution process.

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[10] The purpose of regression testing is 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].

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.

4.2.2.5 Test Completeness

The component integration testing was considered complete for an integrated sub-system when all of the following conditions have 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.

4.2.3 Component Integration Testing Results

The component integration testing was conducted in the 40-ft test bus at the Richmond Field Station. It focused on the interactions and the data communications among the installed components, in addition to verifying that the integrated components still satisfy their respective operational performance requirements. The test environment relates to the hardware, software, and the test support tools needed to conduct the component integration testing. It includes the environment for setup before the testing, execution during the testing, and post-testing activities. The features to be tested are determined based on the system requirement and interface specifications defined in the system and interface requirements. The major components that are integrated include the steering actuator, magnetic sensor modules, the DGPS/INS module, HMI modules, and control computers, as well as 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 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 results of component or firmware problems, the PATH test team then informed the component developers of such issues and returned the component to the component developers 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.

5.0 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 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, operation scenario, and for each bus and for each application. The goals were to establish baseline performance capabilities and to 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 the 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 the system performance and to 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 drivers' 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.

5.1 Test Sites

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

5.1.1 Test track at the LTD yard

To facilitate the system testing, a test track was designed and installed at the LTD maintenance yard. The design considerations include 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 (EB) Walnut Station and the EB Agate Station is generally considered as 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 by 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, where the black line is the main magnet track and the red lines are the secondary magnet track along the two docking curves.

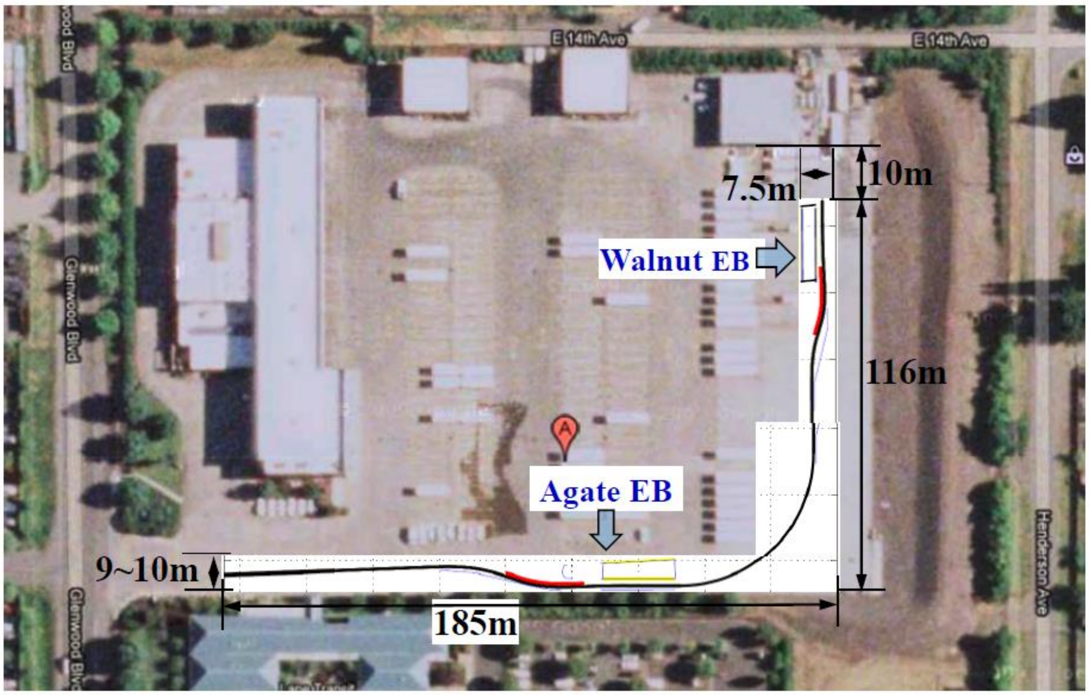


Figure 5-1 The test track at the LTD maintenance yard (Map View)

5.1.2 LTD's Franklin Corridor 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. The LTD's Franklin Corridor EmX BRT route connects downtown Eugene and downtown Springfield, the two main hubs for LTD's system. Figure 5-2 and Figure 5-3 show the street view and the map of the Franklin EmX BRT route, respectively.[11] The four-mile Franklin EmX route uses exclusive single and dual bus lanes for about 60 percent of the route, whereas the remaining 40 percent operates in mixed traffic. Where a single busway lane is employed, both the east 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 feet in

[11] 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 the Gateway Mall and Sacred Heart Medical Center.

width and are separated by an 18-inch curb. Operators can travel up to 45 mph along the corridor. Some portions of the busway employ a grassy median strip.

As stated previously, the VAA applications involve 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[12] were chosen over a stack of four ceramic magnets since a shorter hole-depth was required to avoid re-bars in the concrete busway. The magnets were installed at a spacing of 3 to 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).

Figure 5-2 LTD's Franklin EmX BRT route (Street View)

[12] Each rare earth magnets of 22 millimeter (mm) (7/8 inch) in height and 25 mm (1 inch) in diameter. The magnet was installed about 1/4 inch below the concrete surface.

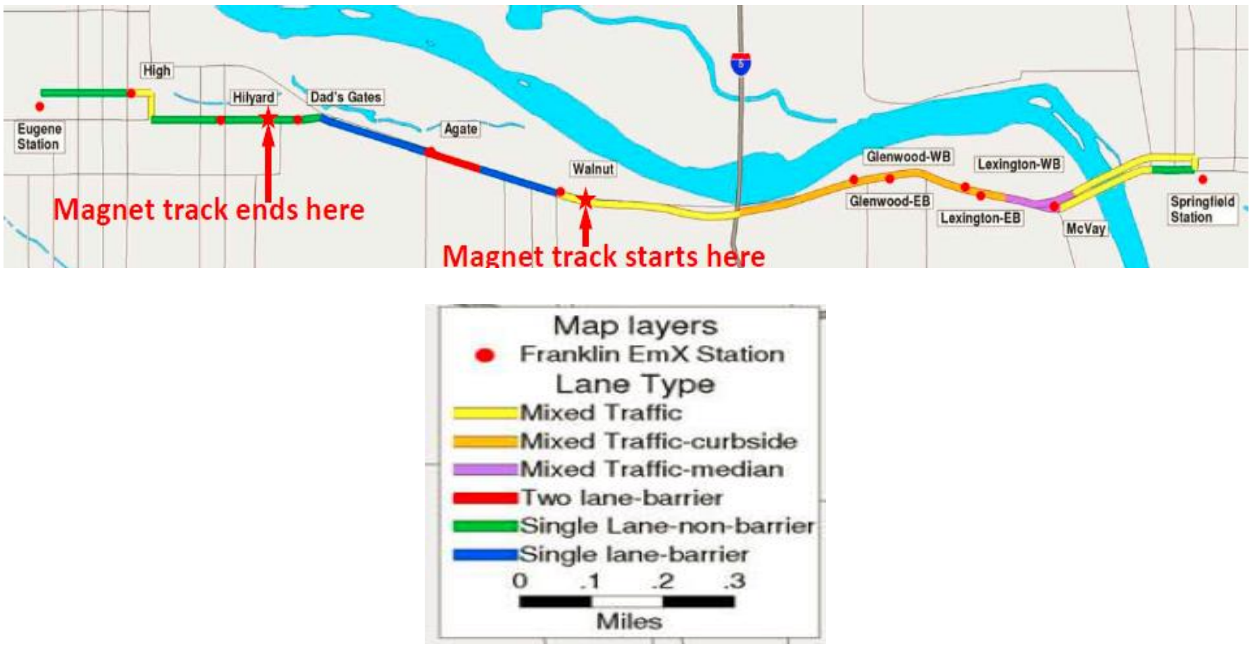


Figure 5-3 LTD's Franklin EmX BRT route (Map View)
(The start and end locations of the magnet track are marked with red stars)

5.1.3 Test Track at the Richmond Field Station (RFS)

As stated, system testing for AC Transit's VAA applications were conducted at a test track at the RFS. **Error! Reference source not found.**4 shows the map view of this test track (shown in blue). This test track mainly consisted of a 57-m straight segment, an 86-degree curve of a radius of 63 m, and a 25-m docking curve (a 3-m straight segment is in 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.

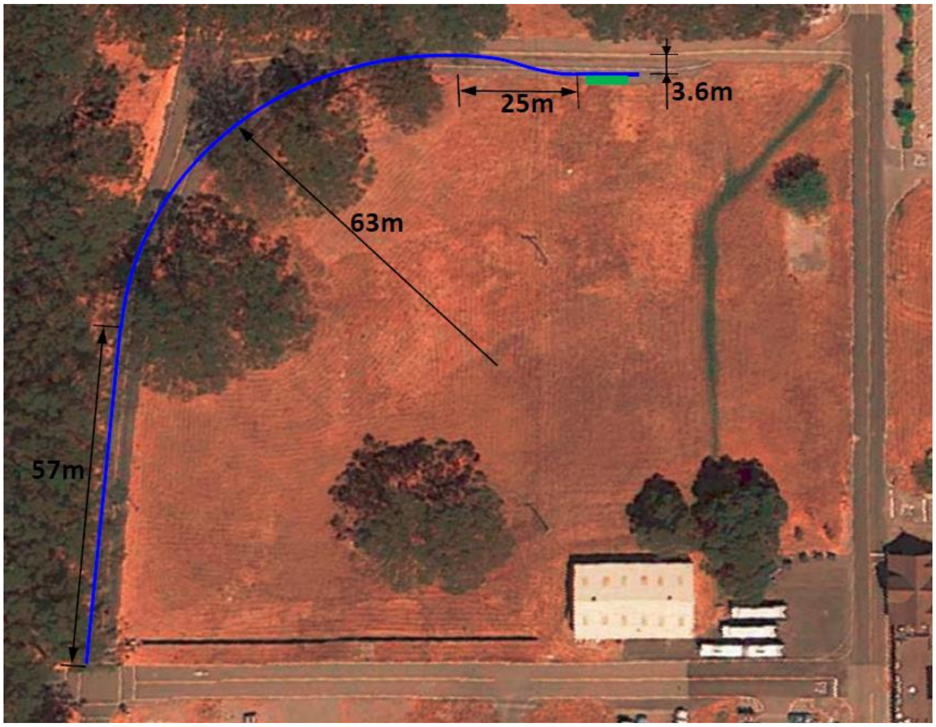


Figure 5-4 The test track at Richmond Field Station (Map View)

5.1.4 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 5-4 shows the map of the AC Transit M Line route. Figure 5-5 shows the MCI coach passing through the narrow toll booth preceding the San Mateo Bridge. The 10-ft wide toll gate has been a challenge for the bus drivers to maneuver the 9.5-ft (8.7-ft bus wide + 0.8-ft mirror) MCI coach safely through the gate. Despite the fact that bus drivers typically need to reduce the speeds to below 5 mph, the mirrors of the bus are still 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 5-4 AC Transit M Line Route
(The start and end locations of the magnet track are marked with red stars)

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 Blvd. and ending at about 328 ft after the San Mateo Bridge toll plaza. Figure 5-6 shows the map view of the magnet track, and Figure 5-7 shows the magnet track through the toll plaza.

Figure 5-5 AC Transit's M Line and the toll booth

Figure 5-6 Magnet track along AC Transit M Line (Westbound HOV lane on State Route 92)

Figure 5-7 Magnet Track at San Mateo Toll Plaza

5.2 Driver Operation and Training

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

5.2.1 VAA System Operations and Driver Interactions

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

5.2.1.1 Basic understanding of VAA operations

Three basic elements are involved in operating the VAA system in the 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.

<u>How to turn on and off the VAA system</u>:

- The VAA system is automatically turned on whenever the bus "ignition" dial is at the ON positions, either 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 at the OFF position.

<u>How to activate (engage) the VAA automatic steering control function</u>:

The VAA steering control function activation is basically a two-step process: 1) the VAA system is in *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.

<u>How to deactivate (disengage) the VAA automatic steering control function</u>:

There are three ways to disengage the VAA automatic control function; they are explained below.

- The 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.

5.2.1.2 Normal operation procedure

Before the VAA bus can be used in automatic control mode, the responsible supervisors from maintenance or operations 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 only be accessible to and turned off by the maintenance or operation supervisors, 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 the bus drivers. If any of the switches is 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 agencies. The following procedure describes the normal VAA operations along the LTD EmX magnetic track at Eugene, Oregon.

- Turn on the bus and drive the bus normally before reaching the magnetic track (westbound from before the Walnut Station, and eastbound from before the 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; the buzzer will sound when the speed exceeds 15% of the threshold speeds.
- The amber LED will also flash when the bus is within 5 feet 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 the buzzers will sound before the bus reaches the last magnets if the driver forgets to deactivate the automatic control.

5.2.1.3 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.

<u>If the fault is detected during automatic control</u>:

- Warning sequence will be initiated: red LED flashing, buzzers beep continuously
- Frequency of the beeps indicates the urgency of the required driver response

- The driver should slow down and take over control as soon as possible

If the fault is detected during manual driving:

- Fault indicator will be on: red LED on and one short beep from the buzzer at the time the fault is first detected.
- No immediate driver response is 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, the knowledge of the consequence of the system failure as well as the proper corresponding response is 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, together with their own 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 it is first detected.
- Driver response: No specific or immediate driver response is 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 the 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 the suggestions from the instructors during the EmX fault testing, the beeping gets faster and faster even when the degraded controller can sustain the system operation. The VAA control will also be automatically terminated when the beeping becomes high frequency.
- Driver response: Driver needs to put his/her hands on the steering wheel upon the warning and prepares for overriding with the steering wheel. He/she can override through the steering wheel at any time. Once the VAA automatic control function is terminated, the warning sound will stop and the red LED will remain lit.

Critical fault:

- Fault type: Multiple component or system failures that results in the VAA system incapable of sustaining safe operation. VAA actuator control is terminated.
- Warning pattern: Red LED flashing with loud, continuous beeping at a high frequency.
- Driver response: Driver should put his/her hands on the steering wheel immediately and take over the steering function right away. Once the VAA automatic control function is terminated, the warning sound will stop and the red LED will remain on.

5.2.2 VAA Driver Training

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

5.2.2.1 Development of the 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 was still a relatively novel concept for U.S. 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, operational concepts, as well as the interfaces between the driver and the automated bus. The development of driver training in this project thus became a combined effort among the VAA system developers, 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 the bus speed as well as activating and de-activating the VAA functions, drivers were responsible for monitoring the operational environment and taking over the steering control functions whenever the driver deemed it necessary or when the VAA system prompted the driver 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 the baseline training materials and generated driver training guidelines, as well as trained the 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 own 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 to adjust the VAA system design and to calibrate the parameters in the HMI design so as to better fit the transit operations.

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

5.2.2.2 Driver Training Procedure Overview

The driver training process consisted of the following two stages:

- In Stage I, the PATH VAA developers first conducted detailed training sessions with a few instructors selected by the transit agencies. The VAA developers continuously updated the training procedure and background information based on the feedback from the instructors as well as the improvements resulting from the VAA system calibrations.

- In 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 procedure. The general group of the drivers who used the VAA system during revenue service were then trained by those instructors with the modified training process.

Instructors and participating drivers

The instructors were selected from the existing instructors of the transit agencies. For this VAA 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 the transit agency. Each job that a bus driver does is a unique combination of routes, times of day, and days of the week. Because of this uniqueness, drivers select their runs in a process known as the bid. In a bid, drivers report one at a time, usually in seniority order, to select their runs at a central location. There are as many bids in a year as their service changes - most transit systems have two to four service changes a year. During the driver-route bidding process that happened prior to the start of VAA revenue service, the transit agencies informed drivers of the route that would have the VAA system testing, and then tried to only assign drivers interested in participating in the VAA operations to the route. However, even if assigned to a VAA equipped route, a driver could still decide whether or not 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 participating drivers who drove the VAA bus signed the consent form and agreed to use the VAA system. In addition, because of the bidding processing, the driver training for the revenue service would be repeated for any new drivers after a new bid process.

Stage I of the 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 the Richmond Field Station. These two test tracks contributed a great deal in the development of the driver training procedure.

It is worthwhile noting that the EmX magnetic corridor includes both exclusive (single and dual) bus lanes with a curb barrier and mixed traffic lanes without a barrier. It crosses 15 intersections. All the curbed sections are narrow (typically 10-ft wide). The corridor is very curvy, with a total of 36 curves (excluding seven sharp docking entry and exit S-curves), eight of them with a radius less than 100 meters (with the smallest radius of 46.6 meters). The bus can reach 40 mph in this corridor. Precision docking is required at six locations (i.e., 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 ever touching the platform or curb, despite variations in drivers' speed profiles. Such a challenging BRT route highlights the important role the yard track played in the introduction of the VAA automated control to the 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 the 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 occur for AC Transit.

Stage II training included the following:

- An (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.
- A few demonstration drives, with the instructor doing the driving.
- Practice driving by the participating drivers with an instructor present. The participating drivers first practiced on the test track and then on the bus route. The drivers might drive as many runs as necessary until they felt comfortable with the system.
- A number of fault testing runs where the instructor turned off the power of various system components, where the driver experienced the failure and practiced the response.

As a part of stage II training, drivers assigned to the VAA bus route were given a consent form to sign. All consenting drivers were required to complete the VAA driver training process 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 the PATH engineers or by an instructor trained in stage I.

The explanation session and the training on the test track typically took less than one working day. LTD (using its more experienced drivers/instructors) designed how the non-revenue training runs would be conducted and determined the completion criteria. After the driver training, the participating drivers were certified to use the VAA system whenever they were scheduled to drive the VAA-equipped bus.

5.2.2.3 Driver Training Background Materials

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

VAA project background

The VAA project background information consisted of the project objectives, participants, technologies used, as well as the test sites and the key tasks and responsibilities.

VAA system descriptions

The VAA system descriptions included the VAA system functional blocks, components installed in the bus, as well as various VAA functions, corresponding performance and possible limitations of the VAA system.

5.2.2.4 Suggested Driver Training Procedure

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

Before the first time with VAA control

- The instructor helps the new driver acquire the basic understanding of the VAA system, the meanings and use of the driver interfaces, the override procedure, normal and emergency operations, as well as the safe operation procedure. This can be accomplished either in the class room with presentation or in the bus with handouts and discussions.
- The new driver rides along with the instructor on the test track to get familiar with the operations as well as the track layout and the simulated stations.
- The new driver practices pushing the manual/auto switches as well as pushing and releasing the emergency button.
- The new driver drives the VAA bus manually without engaging the VAA control on the test track a few times in order to get familiar with the docking curves and the appropriate speeds for each section of the track. During these manual operations, he/she will observe the LED indicators and be able to explain what the indicators mean as well as what his/her proper action should be.

During the first few times with VAA control on the test track

- The new driver drives slowly, identifies the *auto ready* indicator (green LED), pushes the *auto* switch after the green LED is lit, and maintains the control of the bus speed after the blue LED is lit (i.e., under automation).
- The new driver stops at each station's designated stop.
- The new driver practices "override" after the last station.

After a few times with VAA control on the test track

- The new driver can practice driving with different speeds under VAA control, including stop and go, as well as a few times with speeds exceeding the suggested operational speeds.

- The new driver practices override and other means of engaging and disengaging the VAA control under various speeds and operational scenarios.
- The new driver creates and experiences various operational faults under the guidance and explanation from the instructor.

Conducting fault testing after getting comfortable with normal operations

- The instructor helps the new driver to conduct various fault testing by cutting the power off to any one or a combination of the following components:
  - Front magnetic sensor,
  - Rear magnetic sensor,
  - Any HMI processor,
  - Actuator processor, and
  - Any of the control computers.
- The new driver experiences the waning generated by the VAA fault detection and management and practices the corresponding response based on the warning from the VAA system.
- The instructor may start the fault testing by letting the driver know before he/she cuts off the power to the specific components. The instructor may cut off the power to the components without any hint to the driver once the new driver becomes comfortable with the fault responses.

EmX training without passengers

- The instructor determines when the new driver is ready to be trained on the EmX corridor.
- The new driver rides along with the instructor on the EmX track to get familiar with the VAA operations.
- The instructor explains again the safe operations procedure.
- The new driver drives slowly along the EmX corridor, engages the VAA control according to the VAA indicators, follows the magnetic track with conservative speeds, and stops at each station's designated stop.
- The new driver can practice driving with different speeds under VAA control, including stop and go, as well as a few times with speeds slightly exceeding the suggested operational speeds.
- The new driver practices override and other means of engaging and disengaging the VAA control under various speeds or operational scenarios.
- The new driver creates and experiences various operational faults under the guidance and explanation from the instructor.
- Based on the discretion of the instructor, and if the safe environment allows, the new driver may practice some fault testing.
- Finally, the new driver practices the VAA control as if the bus is carrying passengers under regular revenue service operations until both the driver and the instructor feel comfortable of such operations.

EmX revenue service with instructor

- In accordance with the existing LTD training procedure, once the instructor is satisfied with the new driver training performance, the new driver can start the revenue service using the VAA control with the instructor on-board for a number of runs.
- The instructor determines when the new driver can drive the VAA bus for regular revenue service without the instructor on board according to the criteria set by the LTD operation.

5.2.2.5 Driver Training Schedule and Timeline

The LTD VAA-equipped bus started revenue service on June 10, 2013. The official LTD VAA driver/operator training started on April 25, 2013. Prior to that date, two LTD instructors were trained by the VAA developers and supported various testing and performance calibration of the VAA system. Their feedback and suggestions provided valuable information for driver training as well as VAA operations. Between May and October 2013, twenty-three drivers from three bids were trained by these two instructors and all of the trained drivers used the VAA system in revenue service. The VAA bus was assigned to revenue service operations from 6 am to 10 pm every day during the week. All of the drivers assigned to the VAA bus consented to using the VAA system. In September and October, 2014, an additional six 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 would be assigned to the VAA bus operational slot. Thus the VAA driver training had to be repeated for these new drivers. During this period, those new drivers drove the VAA bus under the manual mode at his/her designated time slots before they were certified to engage the VAA control.

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

Official driver training was not completed for the 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-92. 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 the system performance was confirmed. Then, additional drivers from AC Transit would have been trained by the AC Transit instructor.

5.2.2.6 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 that is supported by federal funds must have in place a written assurance to the 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 first answered many questions about the VAA project and the research and organization background. Most of the remaining areas addressed various issues relating to the 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 the various shifts and routes that must be filled. Although the exact process varies by transit agency, it generally involves drivers placing requests and management filling those requests based on some system as defined by the transit workers' union (e.g., priority by driver seniority). Before the driver-route bidding process, the transit agency informs drivers of the route for the VAA system testing. During the driver-route bidding process, the transit agency then tries to only assign drivers interested in participating in the study to the route. However, even if assigned to a VAA route, a driver can still decide whether or not to sign a consent form, be part of the study, and drive the VAA equipped bus.

Screening

Participants must be bus drivers employed by the transit agency, who have volunteered to be assigned to drive a VAA-equipped vehicle. No 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, while participating in the study, drivers were working for their transit agency and entitled to regular and overtime pay as prescribed in their union contract.

Risks

There were two general risks associated with this study to the participants: the risk of being involved in a crash and the risk of a breach of confidentiality. The risk of being involved in a crash during the study could be either 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.

The second risk associated with this study was the risk of a breach of confidentiality. Although the data collected did not include any driver information, the data contained time stamps which could be used in conjunction with the transit agency schedule to identify who was scheduled to be driving the bus.

In order to minimize the risk of crashes related to the VAA system, the system itself was designed with fault detection capabilities and with redundancy of all major components. Furthermore, drivers underwent a training process designed by both the system developer and the transit agencies. The driver training included practices of responding to system failures and taking over the control of the bus. Furthermore, the driver was always in control of the vehicle speed since the VAA system did not impact the longitudinal control of the bus.

Since testing was conducted while drivers were working under the employment of their transit agency, any study-related injuries would be on-the-job and covered under their employer's worker's compensation insurance program.

Confidentiality

The driving and VAA system data that were collected was shared with an independent evaluator, NBRTI, which was selected by the FTA. All data provided to NBRTI was anonymous, without any personally identifiable information of drivers.

Informed Consent

Informed consent was obtained by the instructors at the time 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 attached in the Appendix D for reference.

5.3 System Testing

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

Extensive subsystem and system level testing were carried out first on the test track at the Richmond Field Station 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, as well as for each operating scenario. One critical element of the system testing was fault testing; it included detecting and managing component's, subsystem's and system's faults. The purpose of the fault testing was to ensure that the system could detect faults and safely handle failures. In fact, functional safety is the key prerequisite for public road testing.

5.3.1 System Validation Testing for the LTD Applications

5.3.1.1 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 the VAA technology for testing on the 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 augmentation system -- WAAS[13]) 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 are first conducted on the test track at the LTD maintenance yard and then on the selected section of the LTD's Franklin EmX BRT route. In this process, any modification to the software would need to be verified on the test track first before it could be tested on the public roadway. Appropriate safety measures needed to be in place before the LTD test driver could take it on the EmX route.

5.3.1.2 VAA Performance Characterization on the LTD Test Bus

The goal of the VAA performance characterization is to establish the 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 to establish baseline performance. VAA components were integrated on the PATH test bus and subsystem level tests were conducted to ensure those 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 that the control system could be tuned for the basic vehicle guidance and precision docking functions. After the 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.

Again, the VAA performance characterization of the VAA system on the LTD test bus also included two stages. Firstly, 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 the lane tracking accuracy (lateral offsets), lateral accelerations, and docking accuracy were recorded to facilitate the performance evaluation and the 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 the LTD trainers and they were introduced to the VAA system. Eventually they became part of the development team as research drivers for system testing along the EmX route.

Secondly, after the initial tuning was complete, and the test drivers were trained, testing on the Franklin EmX BRT route started. The daily scheduling of this testing was determined by LTD to minimize interference with normal BRT operations. Again, the performance data were recorded and evaluated, and PATH researchers adjusted the control system parameters to achieve a range of performance characteristics so that the trade-off between tracking accuracy and ride quality (partly according to test drivers' input) were quantified on the LTD BRT route. Since LTD drivers were required to drive the 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.

[13] Wide Area Augmentation System

5.3.1.3 VAA Robustness Validation on the 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 to 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 at a predetermined number of times and performed precision docking at each station where precision docking was planned at a predetermined number of times. The numbers of the times for the above tests were typically determined based on the available schedule of the transit agencies and the operators, the time required for each test, as well as the prior test results. During each test run, the on-board data acquisition system recorded all the performance measurements and the measurements were analyzed to evaluate the consistency and robustness of the VAA system.

5.3.2 System Validation Testing for the AC Transit Applications

5.3.2.1 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 State Route 92, from Hesperian Boulevard to the San Mateo Bridge toll plaza, was equipped for vehicle lateral control, and one 50-foot MCI coach was equipped.

According to the plan, the MCI coach test bus was to use two VAA sensing technologies, individually and in combination: 1) magnetic marker sensing and 2) DGPS with INS. While the magnetic marker sensing is highly reliable and accurate, the 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, as well as 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.

5.3.2.2 VAA Performance Characterization on the AC Transit Test Buses

To establish the 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 to 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 then conducted by PATH researchers for sensor calibration and control system tuning. After the initial verification of the VAA system on the PATH test bus, the VAA components were integrated on the AC Transit test bus and verified for the VAA performance characterization.

The performance characterization of the VAA system on the AC Transit test buses included two stages. Firstly, low-speed tests were conducted by PATH researchers at RFS test track to tune and establish system performance. In this stage, 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 the lane tracking accuracy (lateral offsets) and lateral accelerations, were recorded to facilitate the performance evaluation and the system tuning. The experiences gained from the testing with the PATH test bus as well as from the LTD bus earlier benefited the process. Also as explained earlier, 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. Again, the prior experience gained from the fault testing on the LTD bus made this process easier for the AC Transit bus.

Secondly, after tuning was complete and the 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. Again, the 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 that the trade-off between 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 equipped bus during this testing phase, similar to the process of the LTD applications, the specific driver needed to be trained by the PATH researchers as a research driver beforehand. Due to the resource constraints created by the delay from the contractual issues, the VAA project only finished the first stage of the system testing described above.

5.3.2.3 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 the control parameters had been selected and the 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 their 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 along the HOV lane at speeds up to the normal speed limit at a predetermined number of times. The bus was also to be driven through the bridge toll booth at a predetermined number of times. The numbers of the times for the above robustness validation tests was to be determined based on the following considerations: available schedule of the transit agencies and operators, the time required for each test, as well as the prior test results before the validation tests.

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

5.3.3 System Validation Test Results: VAA Application at LTD

The automated VAA steering control system is to provide 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 includes both exclusive single and dual bus lanes with curb barrier as well as mixed traffic lane without barrier. Moreover, the 3-mile segment crosses 15 intersections and the curbed section is narrow (typically 10-ft wide). The segment is also very curvy, with a total of 36 curves (no including 7 sharp docking entry and exit S-curves) with 8 having a radius less than 100 meters (the smallest radius 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 a 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 and platform) and was sufficiently reliable with all the basic safety measures in place. This section includes the system testing results for the test track at the LTD's maintenance yard as well as along the LTD's Franklin EmX BRT Route (without passengers).

5.3.3.1 System Tests at the Test Track in LTD's Maintenance Yard

The system testing at the LTD test track included the performance testing as well as the safety testing. As illustrated in **Error! Reference source not found.**, the LTD yard track contains replicas of two docking curves, eastbound Agate and Walnut Stations, the two most difficult stations for docking maneuvers. The performance testing evaluated the performance of lane keeping, precision docking, as well as transitions between manual operation and automated guidance. The safety testing involved an extensive fault testing for validating the fault detection and management. The standard fault testing suite included 47 different fault scenarios and their combinations[14]. These basic fault scenarios included failures for each component, subsystem, power, communication, as well as all the VAA system and subsystem functions.

5.3.3.1.1. Lane Keeping and Precision Docking

Figure 5-8 shows the lane keeping and precision docking performance based on twelve consecutive test runs (on Nov. 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 magnetometer sensors and the rear magnetometer sensors. The middle subplot shows the steering wheel angle (in magenta [when in automation] and blue [when in manual driving] lines) as well as the road curvature (in green dashed line). The bottom subplot shows the vehicle speed for each run.

[14] 8 for various magnetic sensors' failures, 7 for steering actuator failures, 4 for yaw rate failures, 8 for CAN, 9 for control computers, 7 for various operational or procedure faults, and 2 for EmX operational problems.

The entry curve of the simulated eastbound Agate Station docking starts at marker number 55, and ends at marker number 102. The bus started the sharp docking curve (a two lane-width lane change with the smallest radii of +45 m and -36 m) at speeds above 20 mph and sometimes kept the speed 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 speed above 15 mph, and finally stopped straight (front and back ends) along the platform at marker number 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.

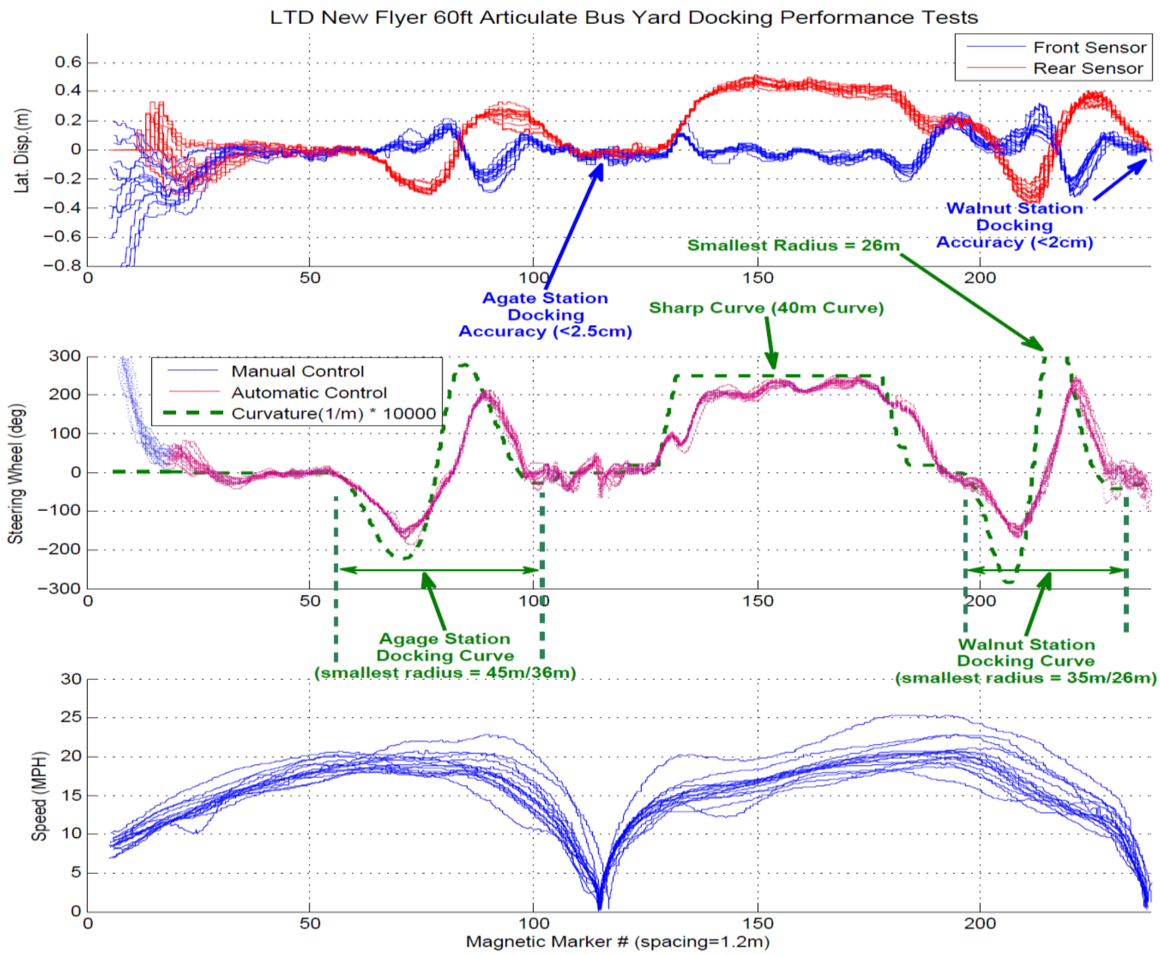


Figure 5-8 VAA lane-keeping and docking performance at the LTD Yard test track

The automated bus then maneuvered through a 90-degree sharp curve with a radius of 40 m and then immediately entered the eastbound 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 two and a half length of the articulated bus. In addition, as shown in Figure 5-8, the bus speeds could reach 22 mph in the middle of the lane change (large steering rate). Despite the variations in vehicle speeds, the bus's lateral deviations remained very consistent from run to run, and the docking accuracy achieved was better than plus and minus 2 cm.

5.3.3.1.2. Automated and Manual Transition

Figure 5-9 shows the data during one test run where the driver frequently engaged and then overrode the automation

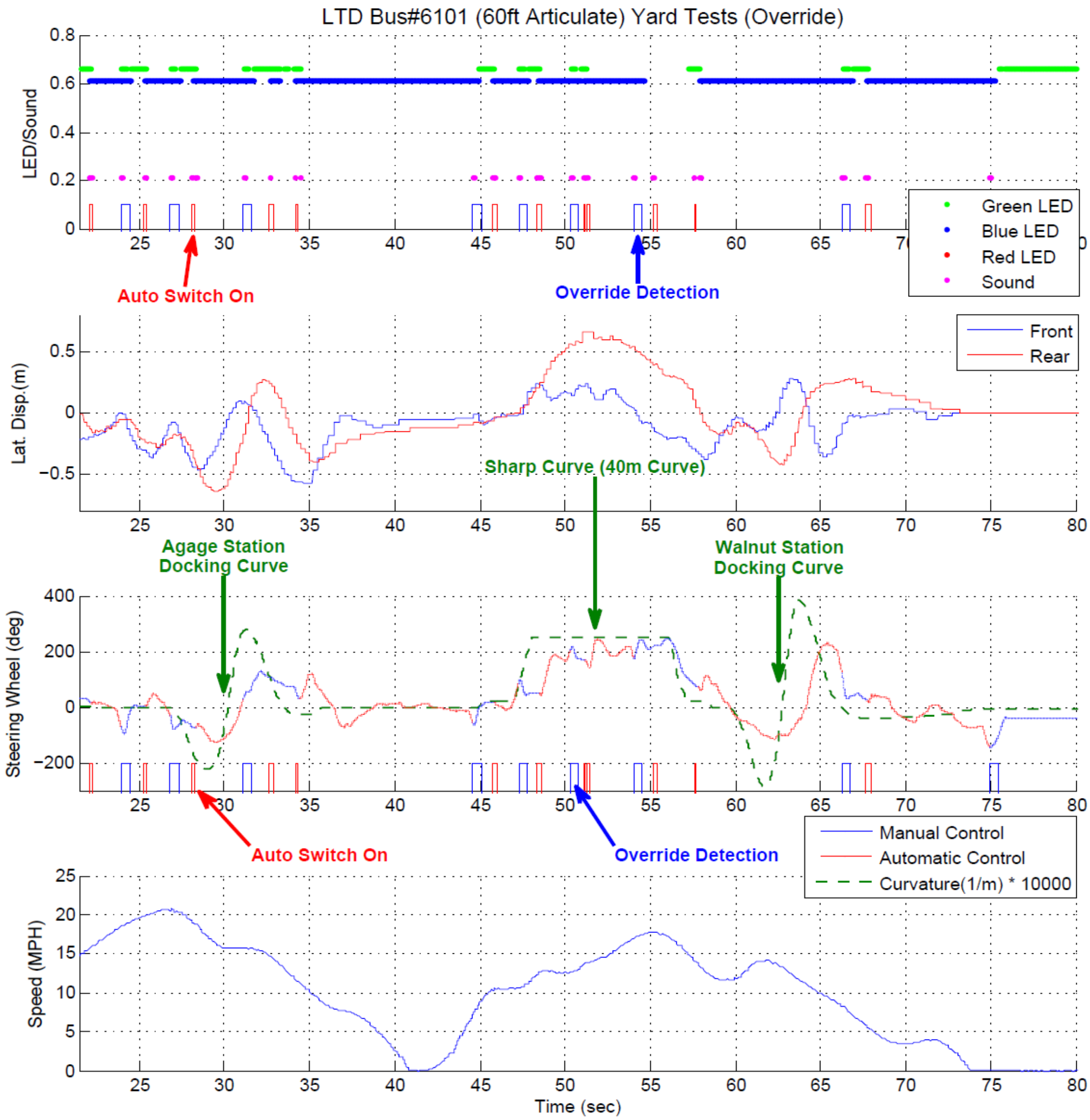


Figure 5-9 VAA system automated-manual transitions using override (LTD yard)

The top subplot shows the LED and sound status. The green and blue dots indicate that the bus is under manual control and automated control, respectively. The red line and blue line 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 second subplot shows the lateral deviation from the magnet track as measured by the front and the rear sensors. The third subplot shows the steering angle of the steering wheel, the curvature of the track, as well as the Auto switch status and the flag indicating override detections. The bottom subplot shows the vehicle speed.

The segments when the bus was under automation are marked both by the blue LED (in the top subplot) and by the red color in the steering angle (in the 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 5-9. The larger lateral deviation is because the bus was typically steered away from the lane center when the driver overrode the automation and many 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.

5.3.3.1.3. Fault Detection and Management

Figure 5-10, Figure 5-11 and Figure 5-12 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 sensor, the rear sensor (Figure 5-10), using the fault-injecting software in the control computers (Figure 5-11), and shutting down the active control computer (Figure 5-12). In each figure, 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 as well as 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).

In the test run shown in Figure 5-10, one of the researchers 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. The researcher 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 third 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 the rear sensors. Finally, 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 control computers 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 that the effectiveness of the degraded controller could be examined.

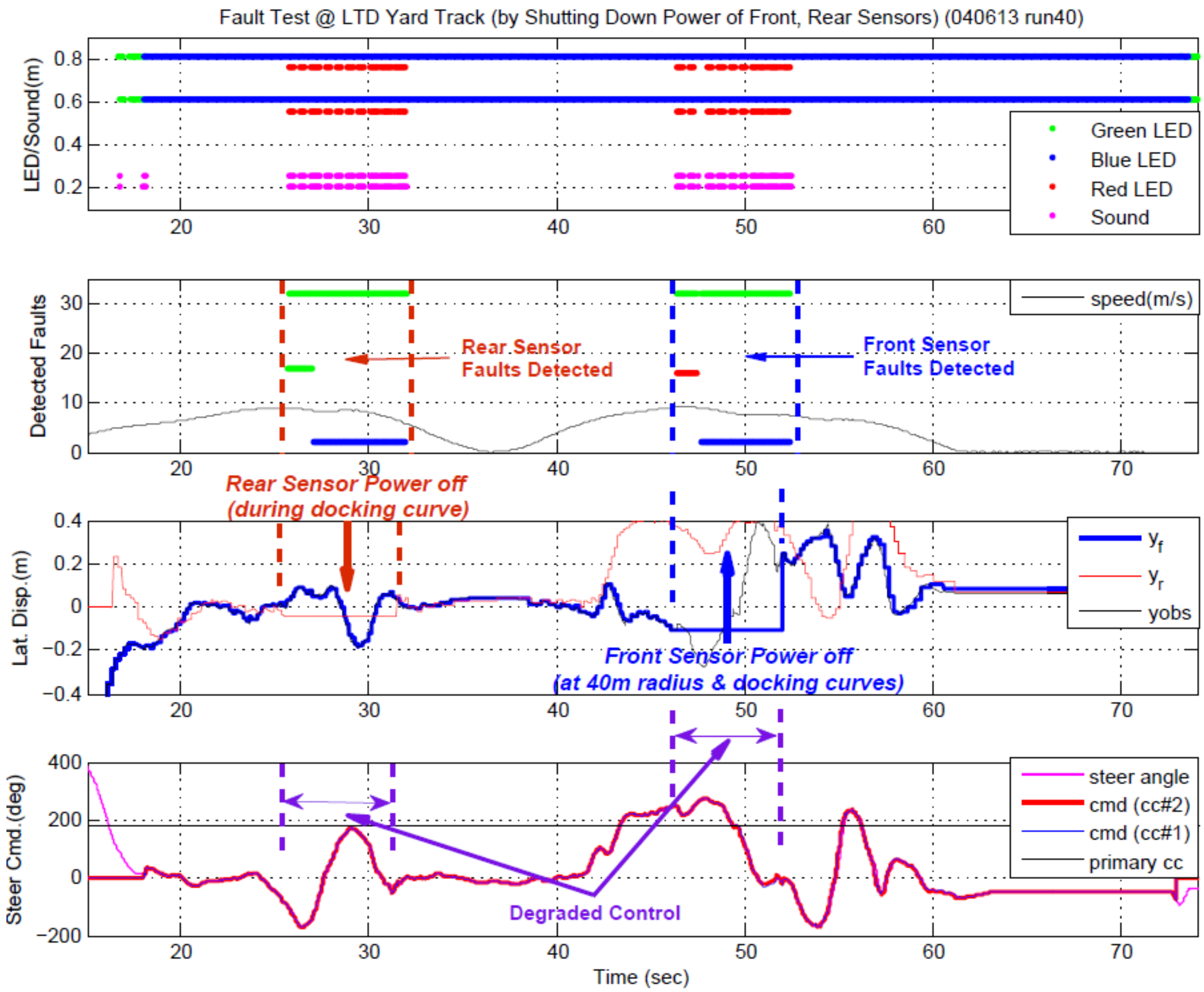


Figure 5-10 Fault testing at the LTD yard track: fault in the rear and front sensors (degraded control set to continuously sustain the automated functions)

Figure 5-11 shows the data of another test run where the software in the primary control computer[15] (cc#2, selected by the researcher at the beginning of this particular 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 time 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. After such fault was injected, the second subplot indicates that the first detection of the fault occurred at 29.95 s, 38.15 s, and 56.1 s respectively for each of these 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 such rear sensor noises. The speed of the fault detection was designed to match the impact of the failure, and this particular rear sensor noise injection apparently did not create an immediate hazardous

[15] The primary control computer is defined to be the control computer that is actively controlling the steering function of the bus. It can be either cc#1 or cc#2. This was particularly true when we were 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 fault. At that time, the primary control computer would then be switched to cc#1 again.

situation (based on the resultant differences in the steering command as shown in the last subplot). The bottom subplot illustrated another major system failure response. First, the primary controller was correctly and successfully switched from cc#2 to cc#1 at 29.9 s (even before the system has issued the 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.

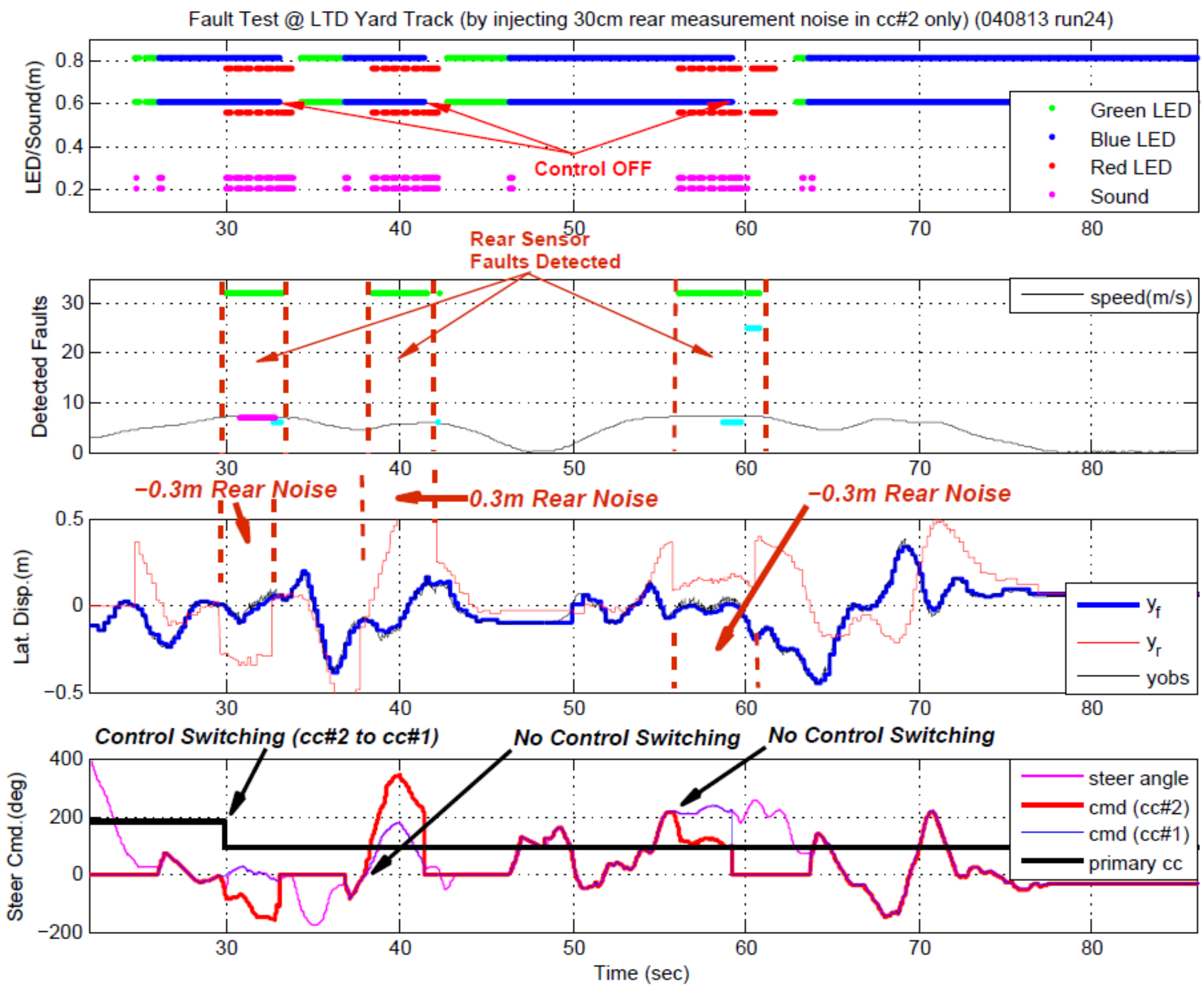


Figure 5-11 Fault testing at the LTD yard track: fault in rear sensor (injecting rear sensor measurement noise in one control computer only)

Figure 5-12 illustrates a test run where the primary control computer (cc#1) was suddenly shut down by the researcher without notifying the driver at time = 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 successful 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 between the two control computers; and 3) the driver could easily took over the control within a few seconds after the warning started.

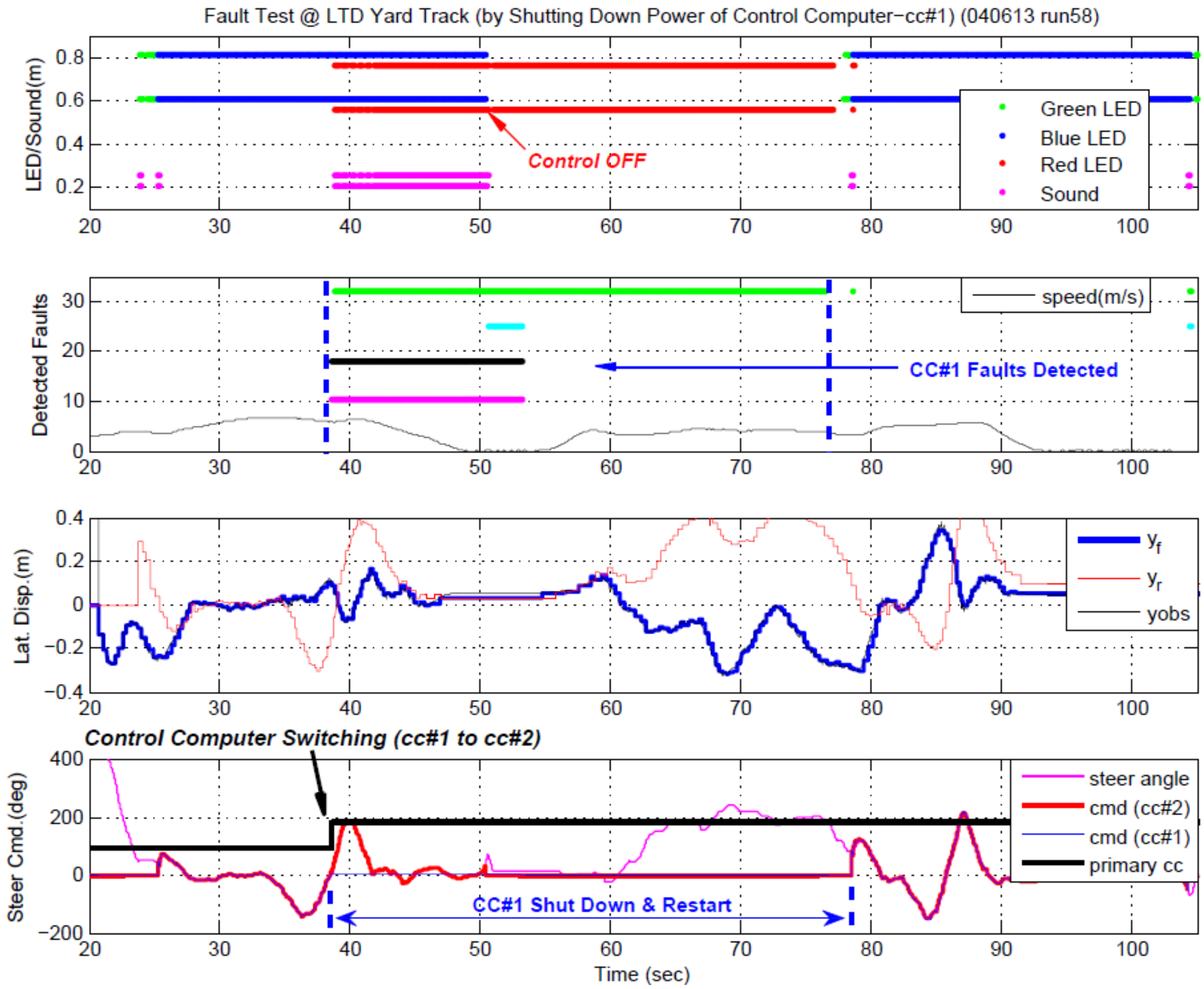


Figure 5-12 Fault testing at the LTD yard track: fault in control computer (faults in shutting down one control computer)

5.3.3.2 System Testing at the LTD's Franklin EmX BRT Route

The system testing at the LTD Franklin EmX BRT route also included the performance testing as well as the safety testing. The performance testing evaluated the performance of lane keeping and precision docking. The purpose of the 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 the public roadway, yard tests were conducted in between system testing on the EmX route to verify any software changes made during this system testing phase.

5.3.3.2.1. Lane Keeping

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

Besides its narrow lane width, the EmX Route is also quite curvy, making it a challenging route for VAA applications. In addition to the sharp docking curves into and out of stations, the westbound VAA-equipped section of the route consists of 19 curves while the eastbound VAA-equipped section of the route 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, the 60-ft articulated bus needs to be "reverse" steered so as to maneuver along the curves without touching the curbs (which has been 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 given in July 2012; however, 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 5-13 shows the lane keeping (and precision docking performance) based on twelve consecutive test runs (in April 2013) in the EmX corridor in the westbound 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.

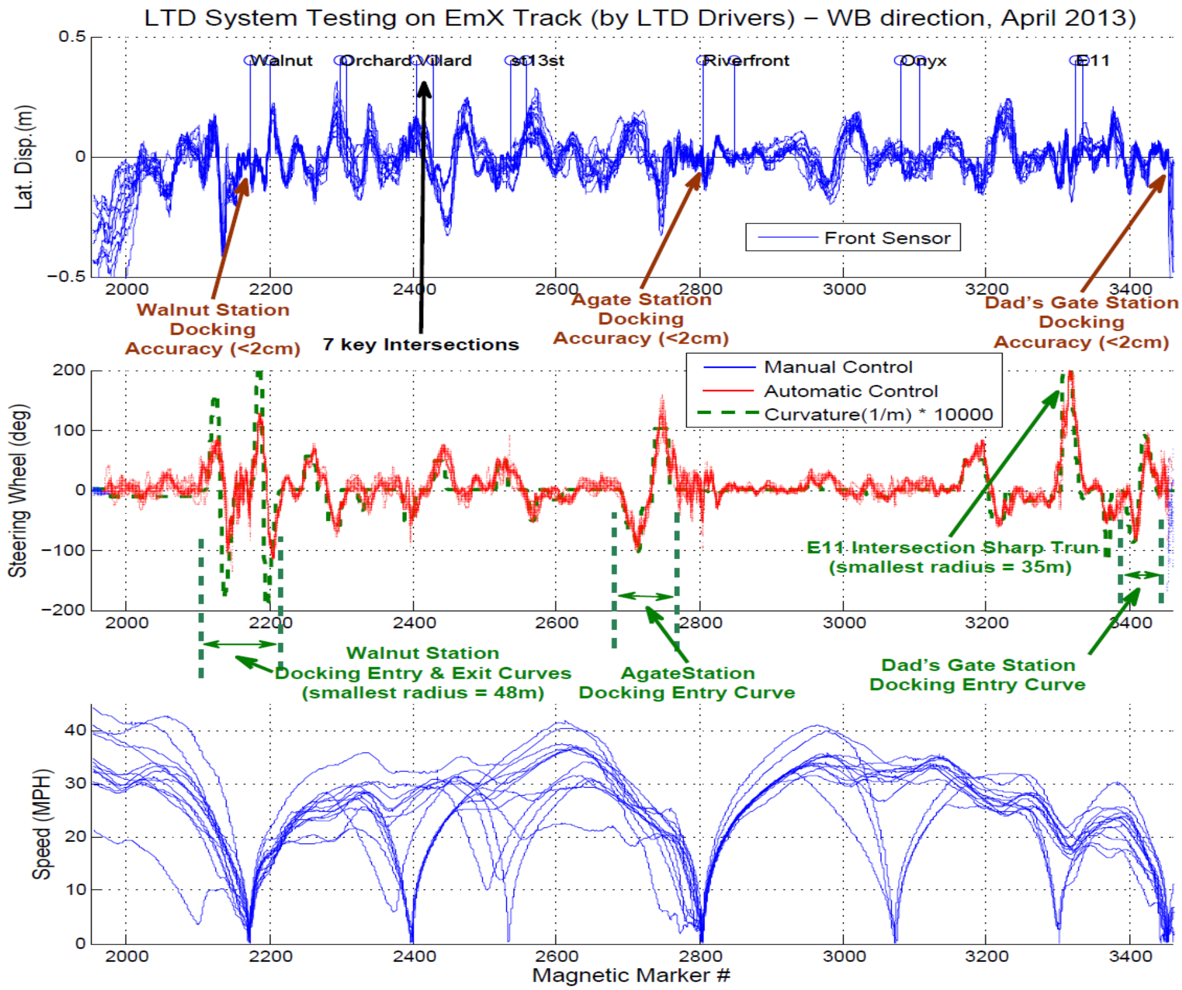


Figure 5-13 Lane-keeping performance at EmX Track (Westbound direction)

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 illustrated that the steering wheel exceeded 50 degrees on the westbound track 16 times on the westbound direction. In addition, the largest steering angle could reach above 230 degrees at the E11 turn. The speeds in the bottom subplot demonstrate that speed variations were very large in this narrow corridor, and the speed 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 resultant standard deviation of the tracking error, excluding the docking entry and exit curves, was 7.9 cm.

Figure 5-14 displays the lane keeping (and precision docking performance) based on twelve consecutive test runs (in April 2013) at the EmX corridor in the eastbound direction. Similar to the westbound direction, the top subplot also 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 degree on the EB track 17 times on the eastbound direction. In addition, the steering angle could reach above 150 degrees 5 times. The speeds demonstrated that speed variations were very large in this narrow corridor and the speed exceeded 40 mph a couple times during the testing. The resultant 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.

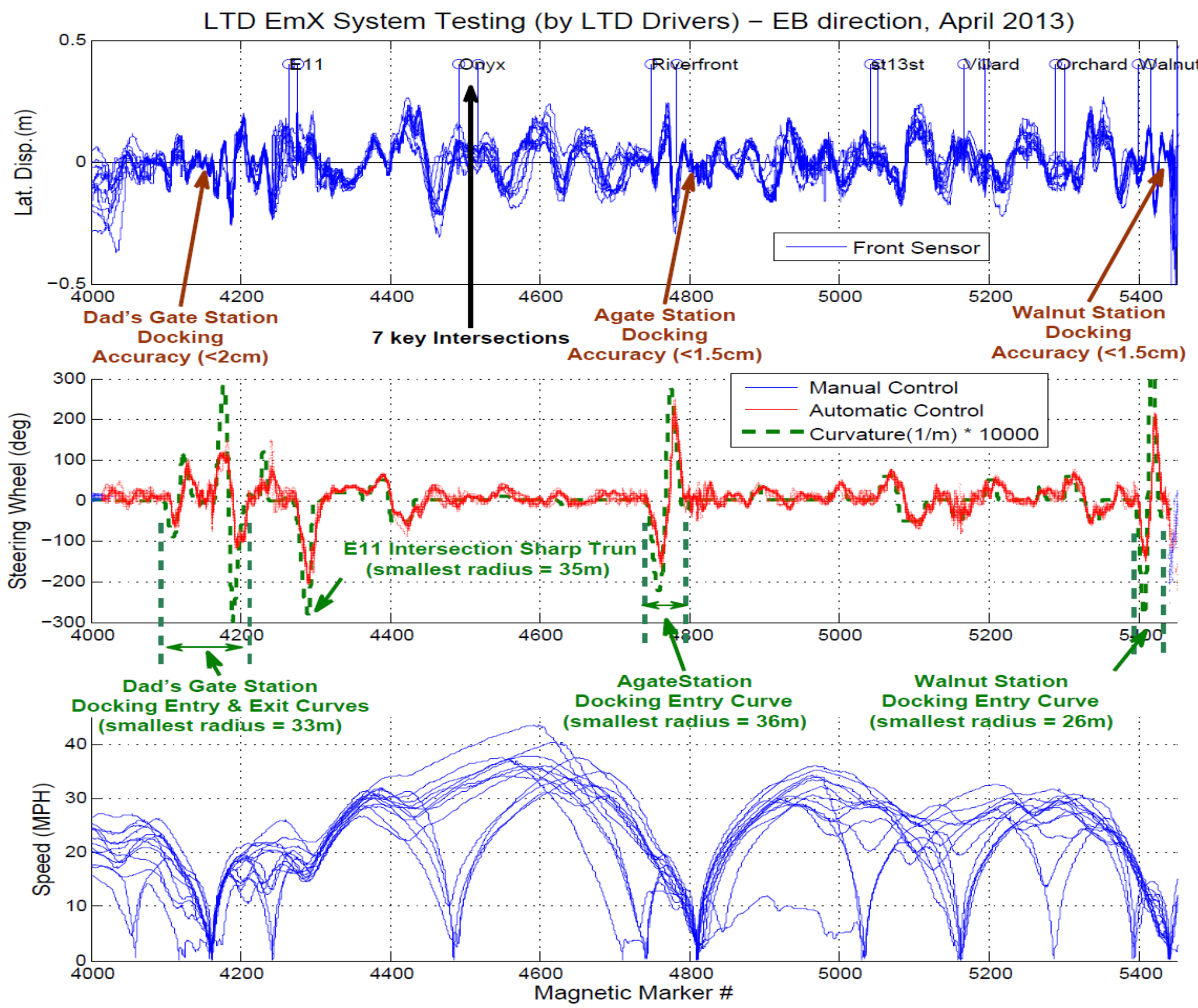


Figure 5-14 Lane-keeping performance at EmX Track (Eastbound direction)

5.3.3.2.2. 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 westbound and one eastbound. Figure 5-15, Figure 5-16 and Figure 5-17 show an aerial view of the stations.

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 eastbound direction (from left to right in Figure 5-15) requires the 60-ft bus to complete a full lane change within a 160-ft longitudinal distance. The docking at Agate Station in the eastbound direction (from left to right in Figure 5-16) requires the 60-ft bus to move about 26 ft laterally (which is more than making two lane changes) within a 223 ft longitudinal distance. In addition, since the roadway widths range from 9 to 14 ft at stations, vehicles have a very narrow area to pull up to the stations.

Figure 5-15 Walnut Station
(a bus is traveling in the westbound direction [from right to left])

Figure 5-16 Agate Station

Figure 5-17 Dad's Gate Station

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

Based on the same twelve round-trip automated VAA runs shown in the previous section, Figure 5-18, Figure 5-19 and Figure 5-20 show the precision docking performance for the three stations (Walnut, Agate and Dad's Gate) in both directions (left figures for westbound, and right figures for eastbound). 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 are the speeds of the bus (controlled by the operator). Those plots exhibit clearly that the docking accuracies for all those stations were within +-2 cm (for both the front and the 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.

For these twelve 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; and
- 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 are:

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

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

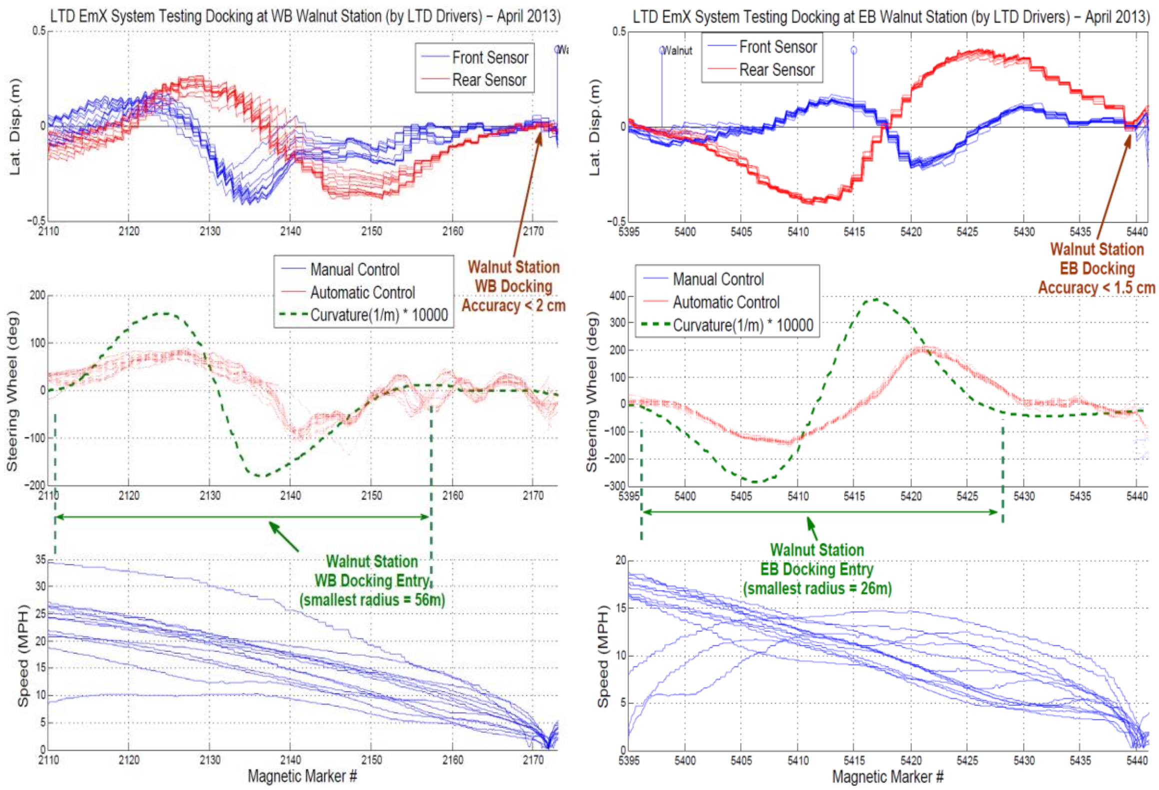


Figure 5-18 Precision docking performance at EmX Track: Walnut Station (WB & EB)

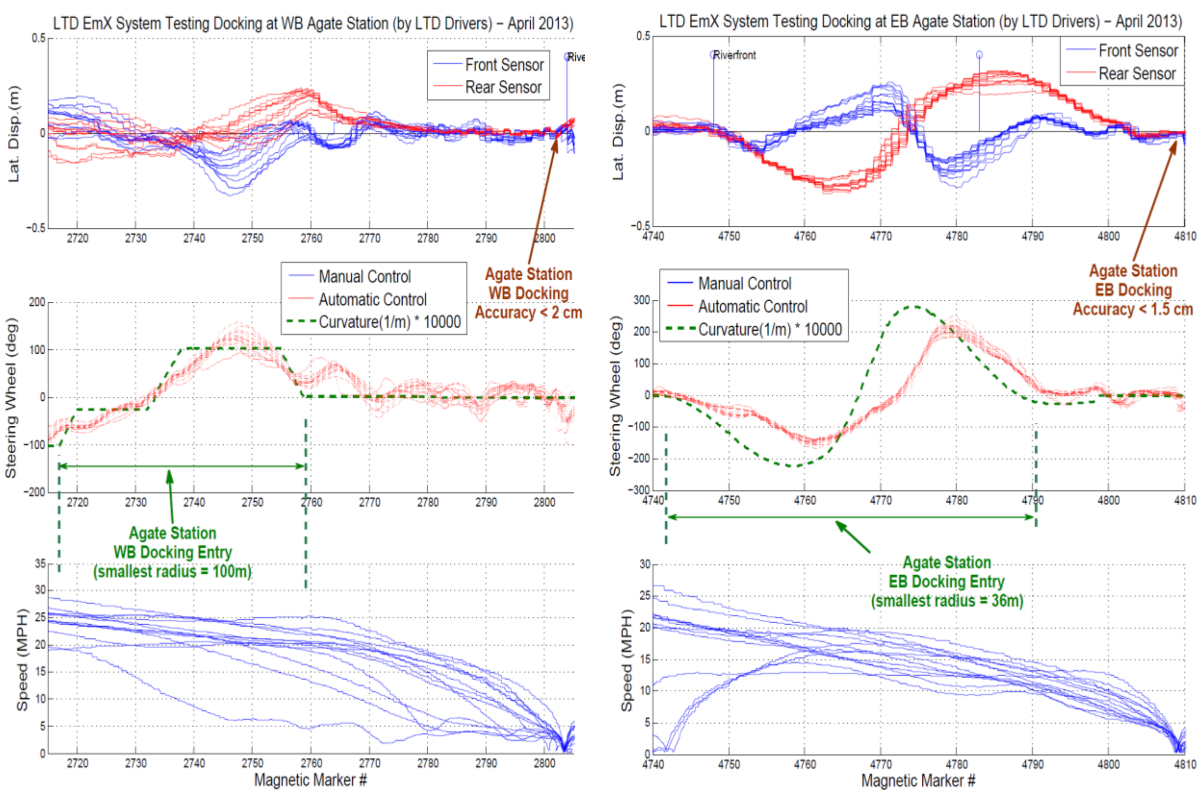


Figure 5-19 Precision docking performance at EmX Track: Agate Station (WB & EB)

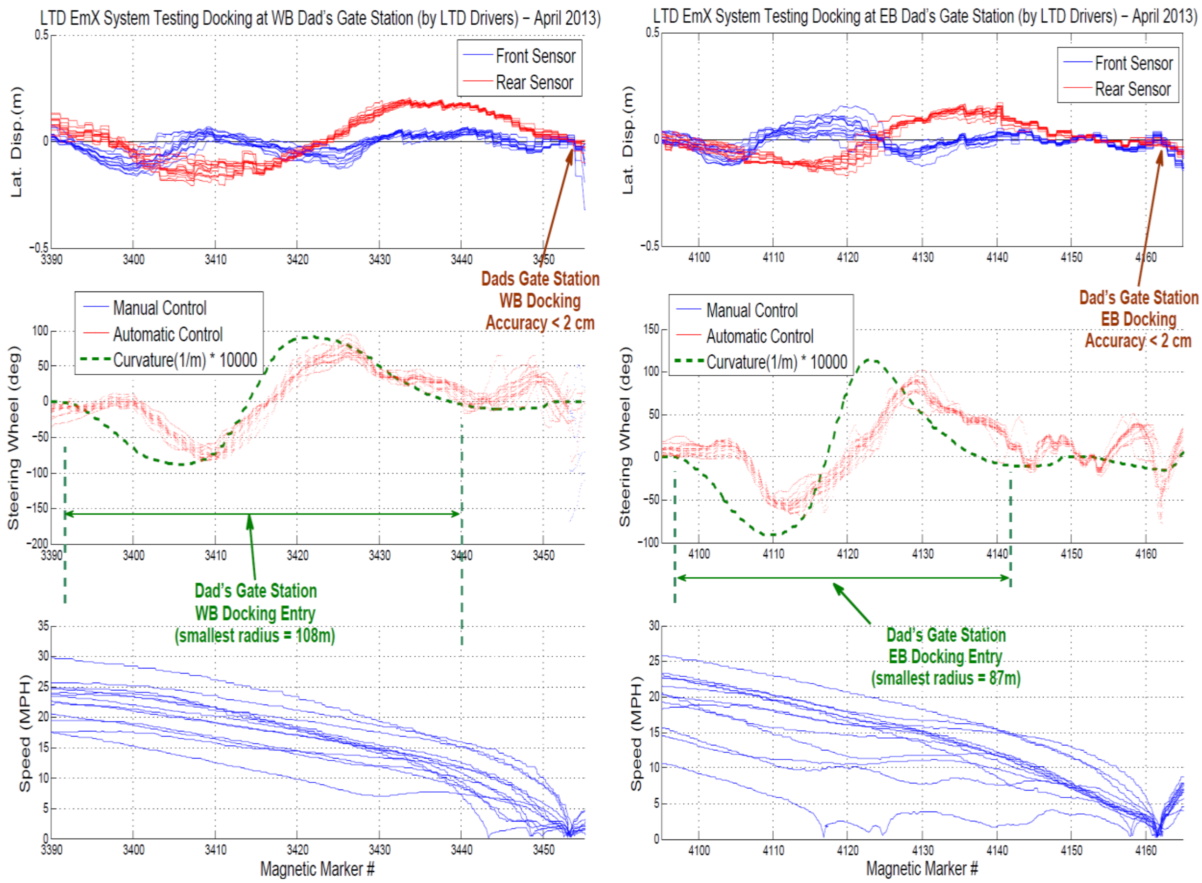


Figure 5-20 Precision docking performance at EmX Track: Dad's Gate Station (WB & EB)

5.3.3.2.3. Fault Testing

As the final validation of the safety and fault testing, a number of basic fault scenarios (by shutting down the power to various components by the 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 as well. Figure 5-21shows the data collected during a fault testing conducted by a LTD operator along the EmX track. The faults were created by shutting down the power of the front sensor, rear sensor, the primary (active) control computer and the 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 as well as 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.

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 immediate warning (not clear in Figure 5-21 due to the limited resolution of the figure).

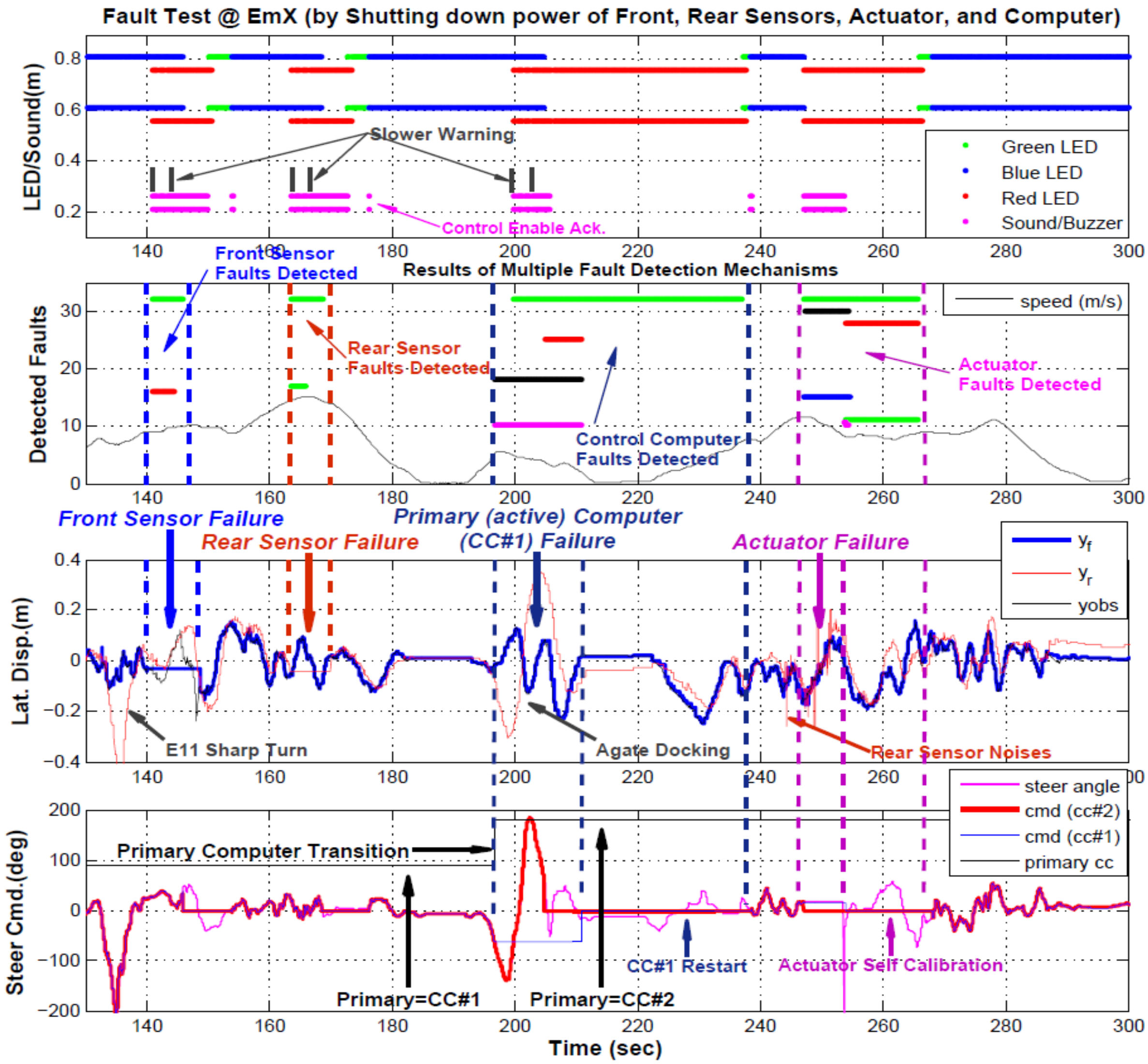


Figure 5-21 Fault testing on EmX conducted by the LTD instructors

5.3.4 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 various contractual issues, in the end, the system tests as well as the operational tests for the M Line along the SR-92 HOV lane and tool plaza were not conducted.

5.3.4.1 System Testing at the Test Track at Richmond Field Station

System testing at the RFS test track included performance testing as well as safety testing. The performance testing evaluated the performance of lane keeping, precision docking[16], as well as

[16] 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 do not include precision docking, testing the control system's capability of precision docking helps ensure that the control system can maintain high-accuracy performance in almost all conditions on the HOV lane.

transitions between manual operation and automated control. The safety testing involved an extensive fault testing for validating the fault detection and management functions.

5.3.4.1.1. Lane Keeping and Precision Docking

Figure 5-22 shows the lane keeping and precision docking performance test results based on ten 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 magnetometer sensors and the rear magnetometer sensors. The middle subplot shows the steering wheel angle (in magenta when in automation and blue when in manual driving) as well as the road curvature (green dashed line). The bottom subplot shows the vehicle speed for each run.

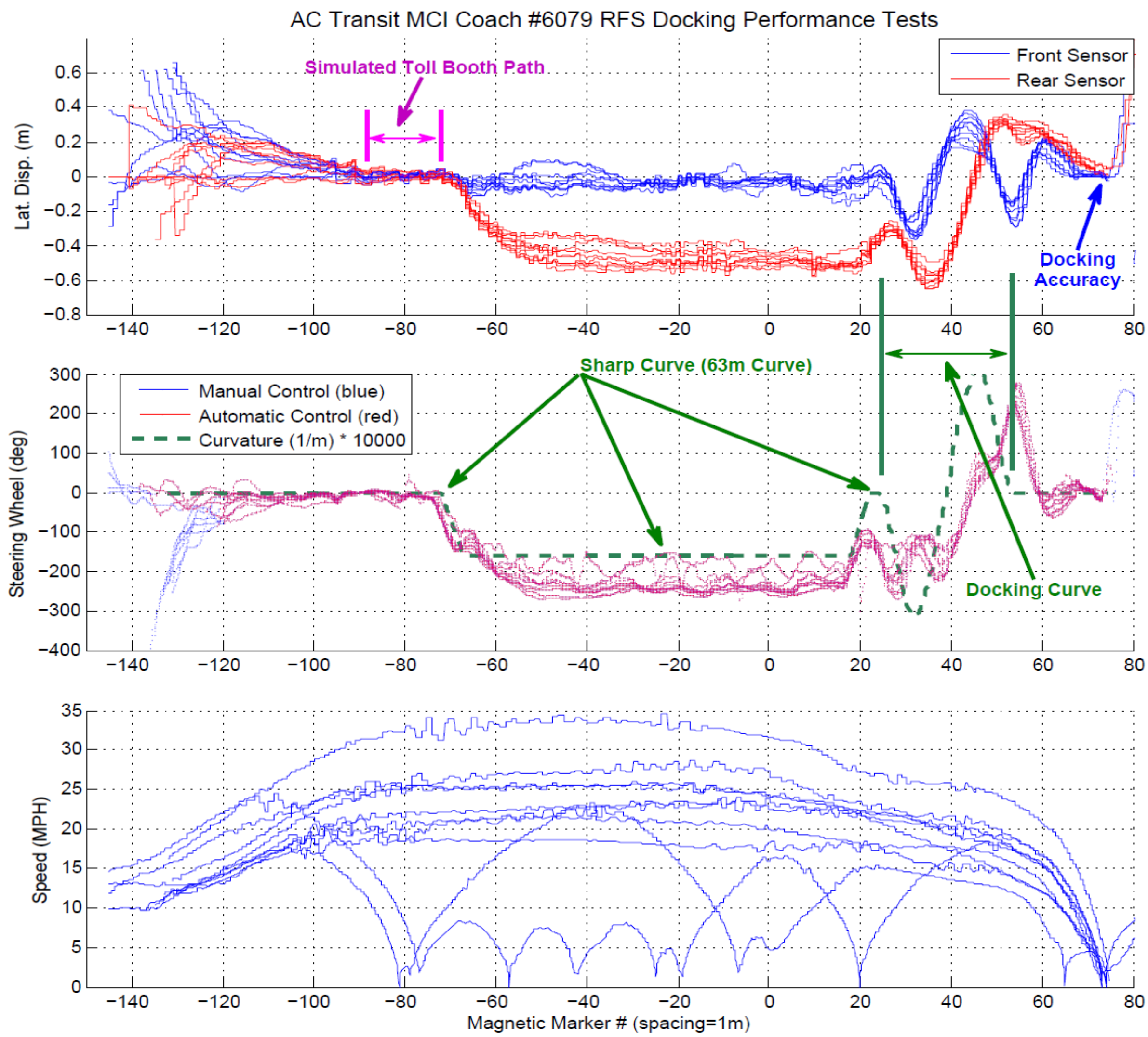


Figure 5-22 VAA lane keeping and docking performance at the RFS test track

As shown in Figure 5-22, 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[17]. Despite the variations in vehicle speeds (including stop and go motions), the bus's lateral deviations remain consistent from run to run.

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

The 25-m docking curve, which was originally designed for testing with passenger cars, is a very challenging docking curve for the 50-ft coach bus. However, the VAA system was able to bring the bus straight and parallel to the platform with the lateral deviation within +/-1 cm consistently. 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 along the AC Transit's M Line, the data demonstrates 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.

5.3.4.1.2. Transitions Between Manual Driving and Automation

Figure 5-23 shows the data collection during one test run where the driver frequently engaged and then overrode the automation. The segments when the bus was under automation are marked. The steering angle in the middle subplot clearly shows that the steering wheel angle was smooth despite the frequent manual-auto transitions. The sensor measurements in the top subplot further verifies that the vehicle moved smoothly and the automatic steering control started bringing the bus toward the road center as soon as it was engaged.

Note that the bus had much larger lateral deviations; the cause of these larger lateral deviations 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 right at the beginning of the docking curve, the VAA system still successfully performed precision docking at the station (as shown in the top subplot).

[17] The measurements of the front magnetometer sensors and the rear magnetometer sensors are about 40 cm to 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 the 50-ft coach bus is essentially a rigid body, when it negotiates a curve the radius for each point on the bus is different. 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 magnetometer sensor bar and rear magnetometer sensor bar are installed at different locations of the bus, their distances to the magnet track (i.e., the road centerline) are different as well. The sharper the curve, the larger the difference based on the geometric relationship.

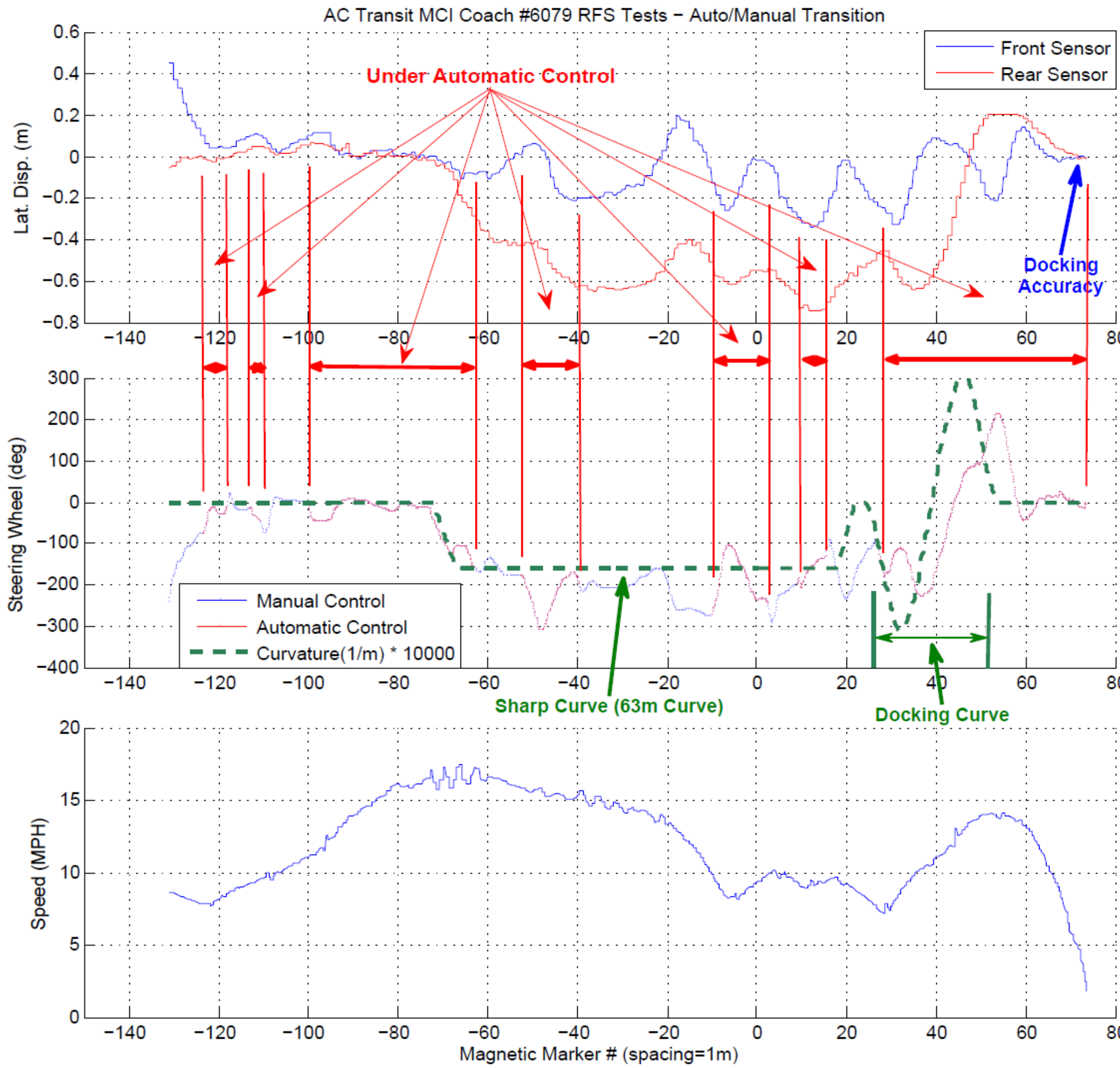


Figure 5-23 VAA system performance in manual-auto transitions

5.3.4.1.3. Fault Detection and Management

Figure 5-24 and Figure 5-25 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 plots 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 is the primary control computer.

In the test run shown in Figure 5-24, 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. The researcher 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 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 (in top subplot) started within 0.1s of the power shut down of either the front or the rear sensors. Finally, the forth subplot illustrated that the degraded controller was effective throughout the period of either the front or the rear sensor bar failure. During this test, the driver was instructed to put his hand on the steering wheel but not to override so that the effectiveness of the fault-tolerant control could be examined.

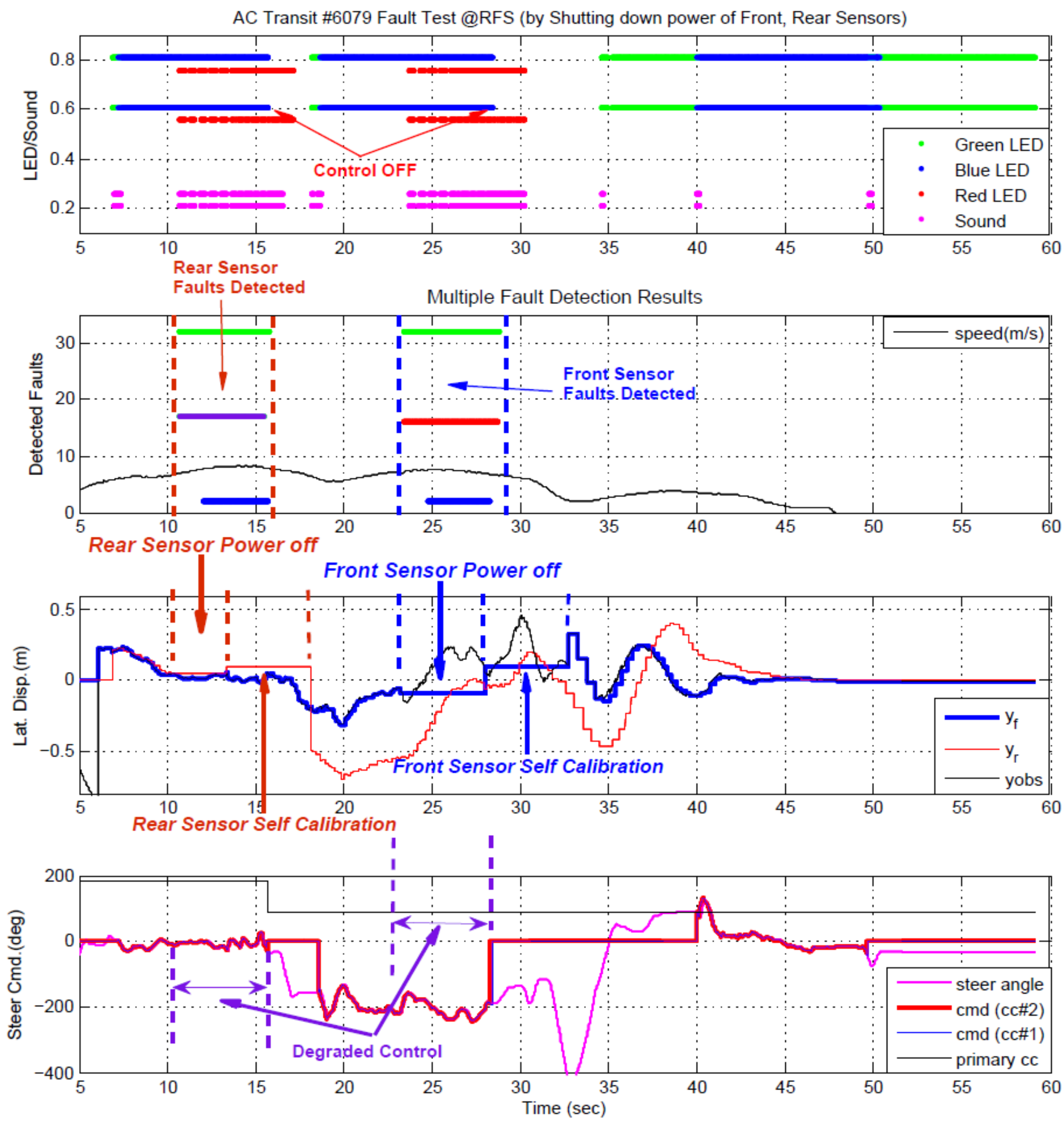


Figure 5-24 Fault testing at the RFS test track: faults in the front and rear sensors

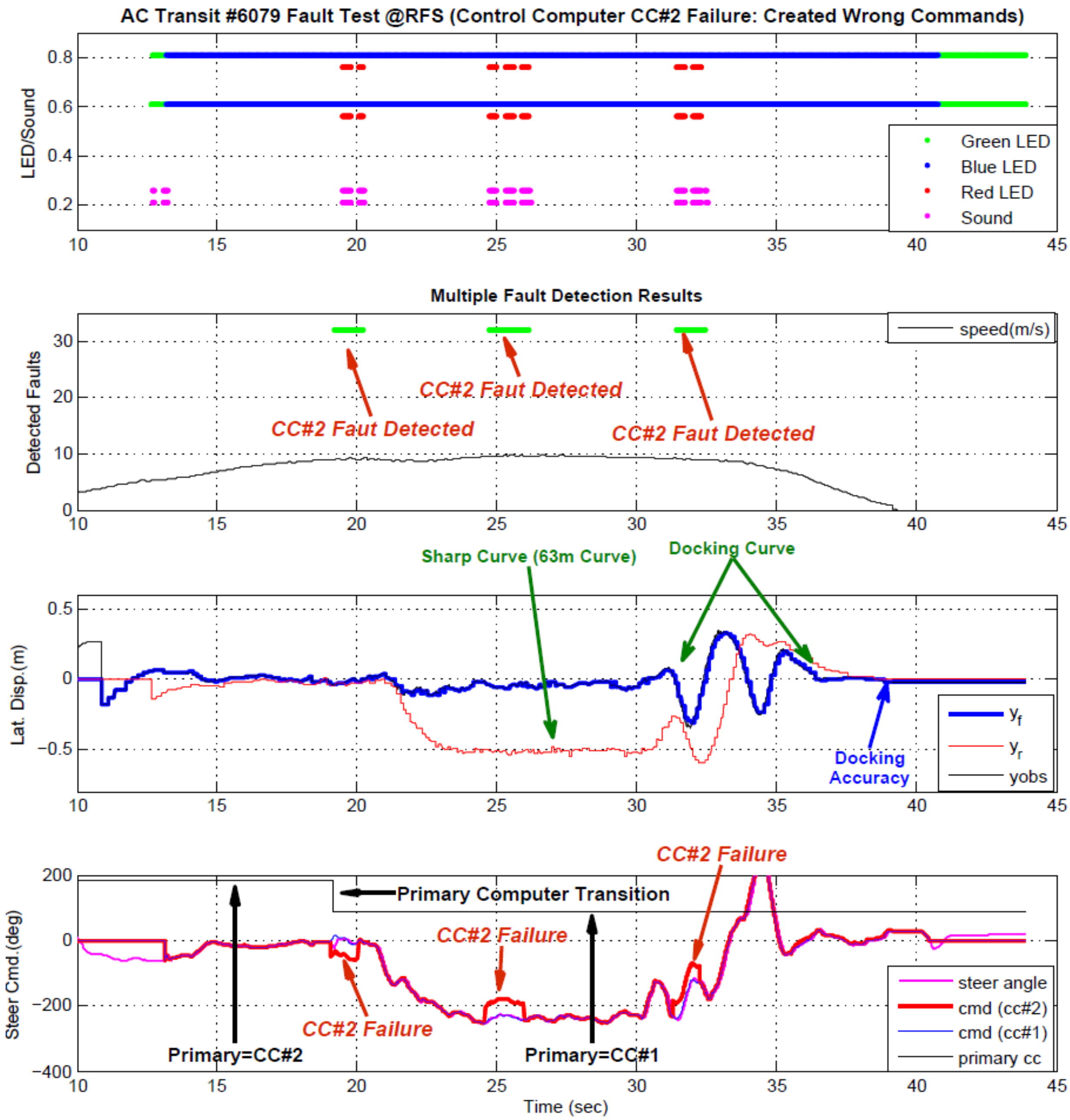


Figure 5-25 Fault testing at the RFS test track: faults in control computers

In the test run shown in Figure 5-25, 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-degree 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 happened 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. They 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 they were first reported at 19.2s, 24.74s, and 31.43s, respectively. Accordingly, warnings (shown in top subplot) were issued within 0.14s 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 19.2s and the primary control computer had 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 the ones between the two control computers, and 4) the driver easily took over the control within a few seconds after the warning started.

5.4 Field Operational Testing

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

To achieve those general goals, both the field operational tests at the AC Transit site and LTD site aimed to provide quantitative measures of the 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 transit ways, especially if these 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 this FOT as a critical step toward more extensive use of VAA technologies on future bus routes and service.

5.4.1 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 passengers' perceptions of the VAA system
- To understand the impact of the VAA technologies on maintenance

In order to assess if the objectives had been met, the FTA selected NBRTI to conduct an independent evaluation of the VAA Demonstration.

5.4.2 The Data to Be Collected

According to the VAA program goals, data relevant to those objectives needed to be collected and analyzed. The following are examples of data that were 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 passengers' perceptions.

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

The data to be collected can be categorized into two main categories: objective dataset and subjective dataset. The objective dataset includes quantitative performance data that describes the operation of the vehicle and the VAA system, as well as the data related to the operation environment and maintenance. The subjective dataset includes qualitative perceptions and experiences of the bus operators and passengers.

5.4.2.1 The Objective Dataset - Quantitative Performance Data

The VAA system incorporated an on-board data acquisition system, which recorded 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 to identify, diagnosis, 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:

- 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.

5.4.2.2 The Objective Dataset – Transit Property Record Keeping

In addition to the quantitative performance data, the objective dataset also included the data related to the operational 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)

5.4.2.3 The 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

5.4.2.4 Data Collection Mechanisms

5.4.2.4.1. Data Collection Instrumentation

The quantitative performance data were collected by an on-board data acquisition system, which 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 all the time that the vehicle electrical system was on, without requiring any special actions by the driver or maintenance staff.

Due to the 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. PATH team also developed software to preprocess the data and provided the aggregated data to the independent evaluator for analysis.

5.4.2.4.2. Subjective Data Collection

The subjective data was 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.

5.4.2.5 Analysis of System Performance Data

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

5.4.2.5.1. Tracking Accuracy

The 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 – mean, standard deviation, and maximum offsets versus distance along the route.

The 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 locations and these portions of data could be analyzed to provide statistics for docking accuracy, including the mean, standard deviation, and maximum lateral offset for each docking station as well as those for all docking stations.

5.4.2.5.2. 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's manual control with the lateral accelerations under VAA steering assist. The aggressiveness of curving behavior is indicated by the peak lateral accelerations as a function of location along the route.

5.4.2.5.3. 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. In order to understand the factors that may limit system robustness, it is necessary to associate the 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, these independent measurements should be used as sorting criteria to group the tracking error data so that they can be compared. For example, the times during the operational tests when the crosswind speed exceeds 25 mph should be identified and the tracking error data for the buses driving at these times should be analyzed and compared with the data for times when this threshold value was not exceeded. Similar analyses should be done 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 variations in the standard deviations across the board, there may be no need to perform the above analysis.

5.4.2.5.4. 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 the experimental data by computing its inverse, identifying the amount of time that 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.

5.4.2.5.5. Safety-Related Observations

Safety concerns should be identified both quantitatively and qualitatively, and those measures should be 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.

The quantitative measures do not a priori mean that there has been a safety problem, but they indicate conditions that should be investigated by the analyst to determine whether safety problems indeed occur, 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.

5.4.2.5.6. 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, were to be explored individually by a skilled analyst studying the full range of recorded data available.

5.4.2.5.7. 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 that 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).

5.4.3 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” versus “without” comparison, which is 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.

5.5 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, Oregon. 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: EmX route testing without passengers. Since the results of the second part of the operational tests -- revenue service -- include the engineering and statistic results for evaluation, they are reported separately.

During operational testing without passengers in May 2013, 119 round trips (and six 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.

5.5.1 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. Our measurements indicated that the horizontal gap was usually between 3cm and 5cm at both the front and the rear tire locations at these stations except the west-bound Walnut Station. Figure 5-26 through 5-30 show typical docking performance. To achieve the same horizontal gap at the west-bound

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 drivers' perception, precision docking at west-bound 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 5-26 Precision docking at Walnut Station (east-bound)

Figure 5-27 Precision docking at Agate Station (west-bound and east-bound)

Figure 5-28 Precision docking at Dad's Gate Station (west-bound and east-bound)

5.5.2 Lane Keeping Performance

Table 5-1 lists 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 listed. 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		
	West-bound trips (119 trips)	East-bound trip (125 trips)	All trips	West- bound trips (114 trips)	East-bound trips (108 trips)	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

Figure 5-29 shows the lateral positions of all of the trips the VAA-equipped bus made 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; these lateral positions 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 while the bottom plot shows the lateral positions for trips with manual driving. In both plots, the positions in blue without either red or green dots correspond to the lateral positions on docking curves. Since we are focusing on lane keeping performance, these lateral positions on docking curves were excluded from the analysis. The red dots in the top plot marks the lateral positions under automated lane keeping control, while the green dots in the bottom plot marks the lateral positions under manual lane keeping. The number of trips with automated steering is comparable with the number of trips with manual driving.

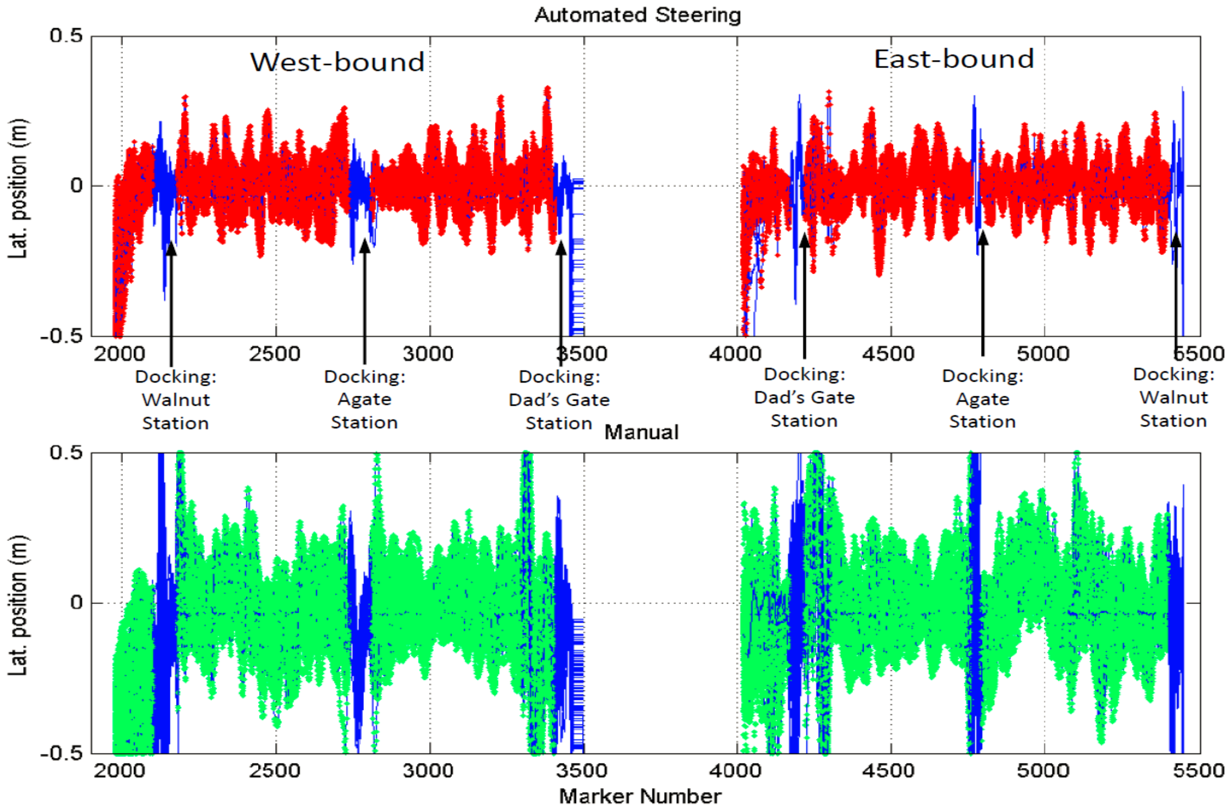


Figure 5-29 Comparison of lateral positions (automated steering vs. manual driving)

From Figure 5-29, 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 lane and providing a relatively smooth ride in narrow and curvy pathways.

5.5.3 Operational Testing Data Examination

To help explain how the automated system was operated and performed, this section presents data of a west-bound run and an east-bound run 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 5-30 shows the lateral position (relative to the magnet track) measured by the front sensor bar, vehicle speed, as well as the status of the LED lights and the auto/manual toggle switch for the first 4 seconds of the selected west-bound run. The time "0" corresponds to the time when the bus detected the first magnet about 840 feet (256 m) before the Walnut Station. As shown in Figure 5-30, the amber LED was lit at the beginning, indicating that the automatic system is 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 is ready for transition. A beep was issued at the time the green LED was lit to inform the driver that the system is 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.

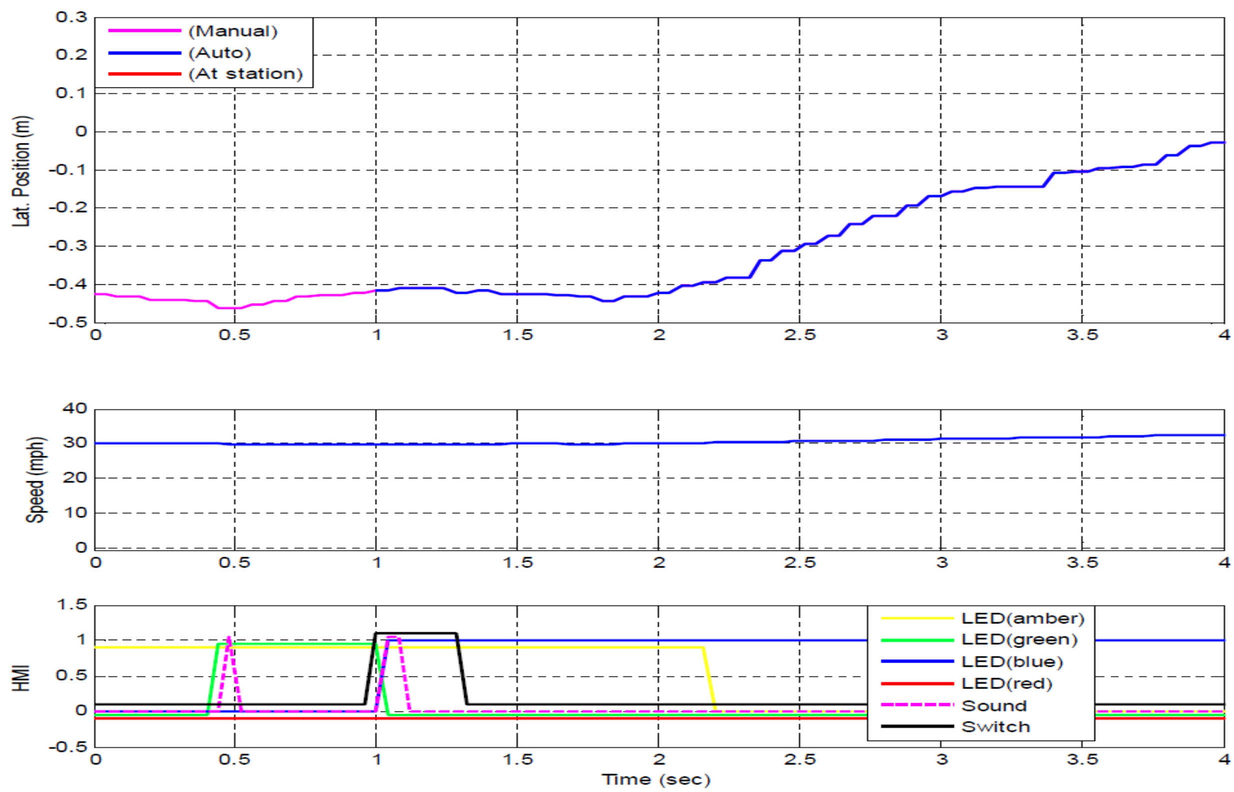


Figure 5-30 EmX WB run: lateral position error, speed, and HMI LEDs & switch (time based - first four seconds)

Figure 5-31 shows the complete time traces of the same signals (lateral position, vehicle speed, LED lights, and switch) shown in Figure 5-30. At around 7~9 seconds, the bus speed went over 35mph and the amber LED blinked to provide speed warning to the driver. At around 30 seconds, the bus arrived at the 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 St. 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 St. 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 Ave., the bus made a sharp left turn onto E 11 Ave. 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 Dad's Gate Station for 11 seconds, the driver overrode the automatic system by taking over the steering wheel before he/she drove the bus away from Dad's Gate 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.

For this west-bound run, the bus was under automatic control almost the entire run. Except for the sharp left turn onto E 11 Ave., the lateral positions (with respect the magnet track) never exceeded 20 cm. The lateral positions[18] 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 is 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 Blvd to E 11 Ave. (or from E 11 Ave. to Franklin Blvd for the east-bound run) has a minimum radius of 46.6 m. Drivers 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 was initially designed to follow the magnet track with higher precision. However, drivers and even 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 so as 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 5-31 shows the performance of the final VAA system, where the lateral deviations were within 20 cm (except on the sharp turn onto E 11 Ave. to reduce the offset tracking on rear end of the bus.).

Figure 5-32 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.

[18] A position (or negative) lateral position indicate 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 the bus is closer to (or farther away from) the platform than the desired position.

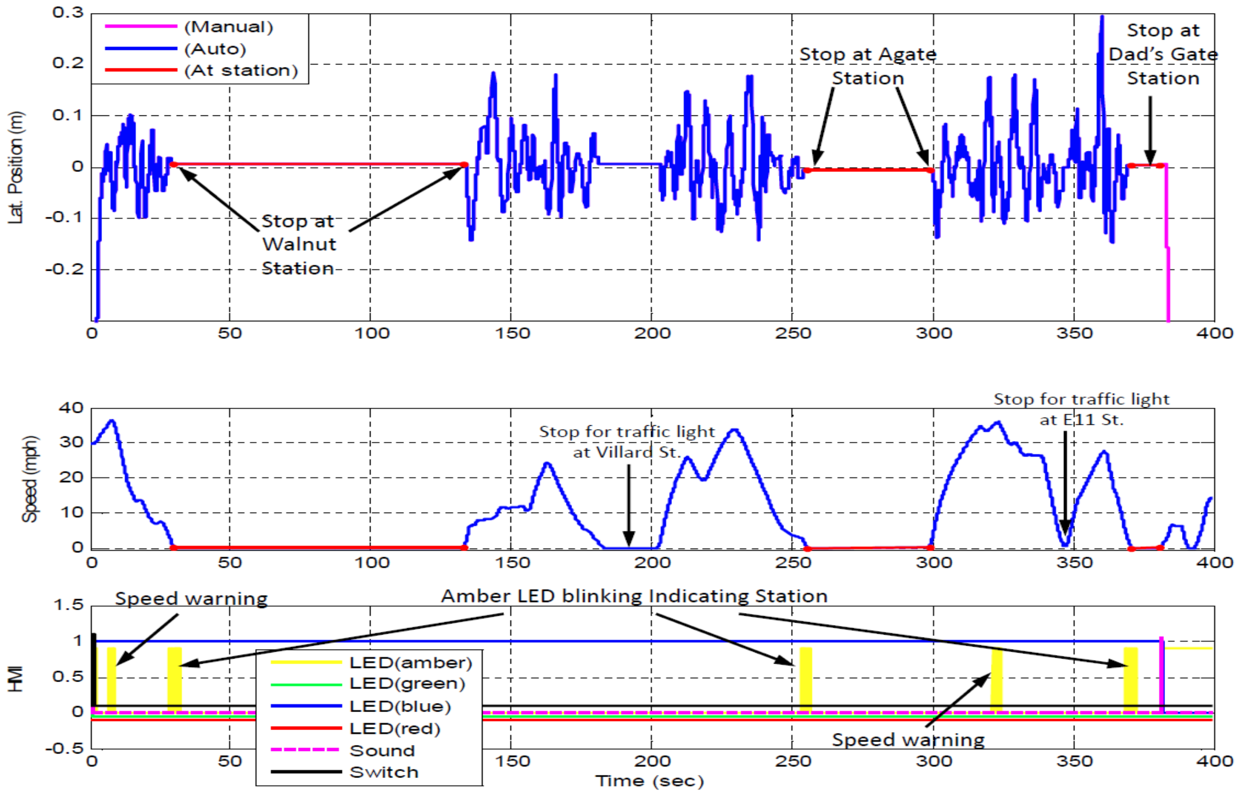


Figure 5-31 EmX WB run: lateral position error, speed, and HMI LEDs & switch (time based)

Figure 5-33 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 the rear magnetometer sensor bars. As shown in Figure 5-33, the vehicle angle was within 3 degrees 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 Ave. (at around 1470 m). Moreover, the vehicle angle quickly converged to smaller than 0.1 degrees once the bus completed the docking curve and stopped at the stations, indicating the bus was almost parallel to the platform.

Figure 5-34 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 5-32) and vehicle angle (Figure 5-33), at the transition between the manual driving and the automatic control indicates smooth transitions. The steering angle on the EmX route was in general less than 100 degrees in either rotation direction. The steering angle reached its maximum of 213 degrees during the sharp turn from Franklin Blvd. to E 11 Ave. 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.

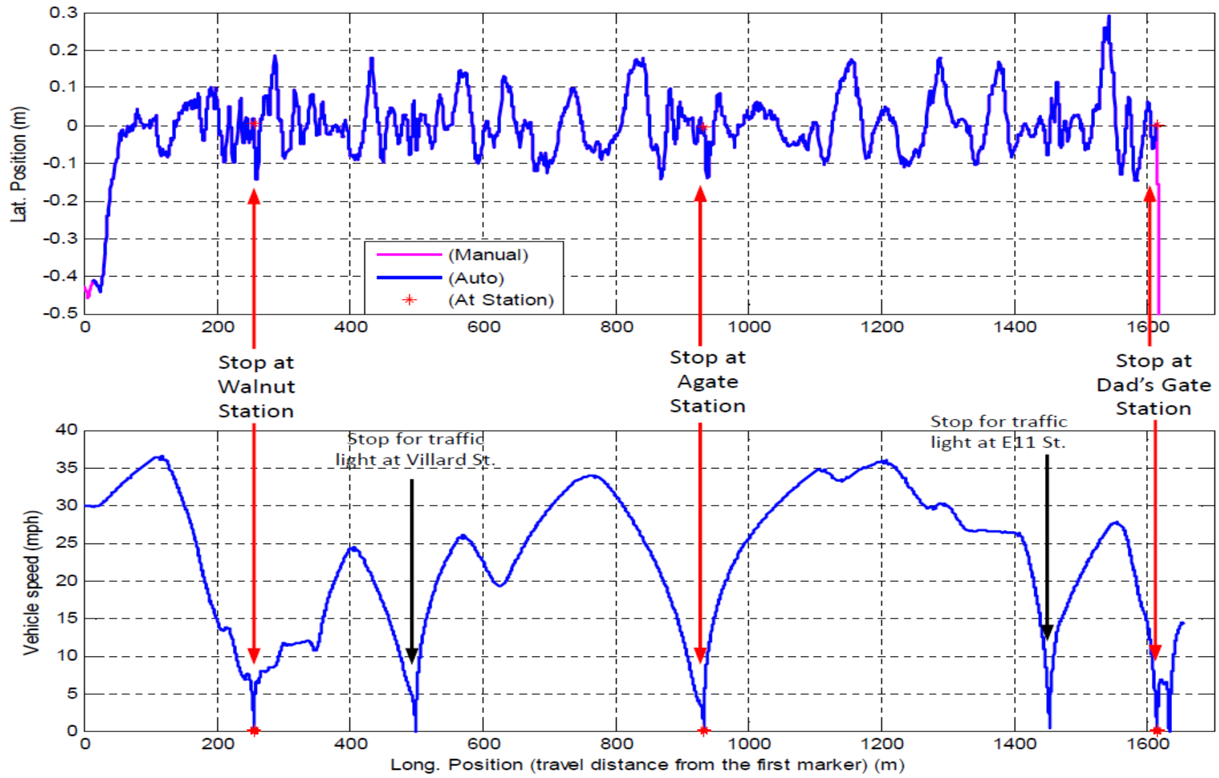


Figure 5-32 EmX WB run: lateral position error and speed (distance based)

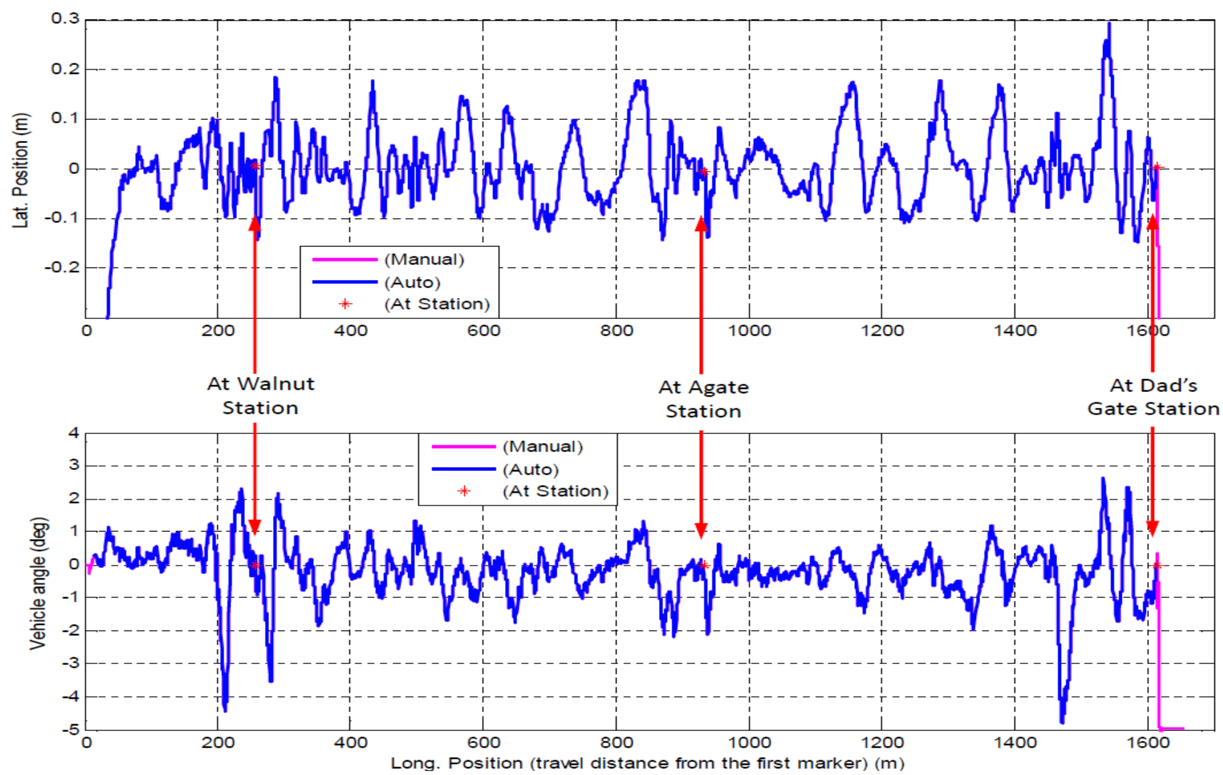


Figure 5-33 EmX WB run: lateral position error and vehicle angle (distance based)

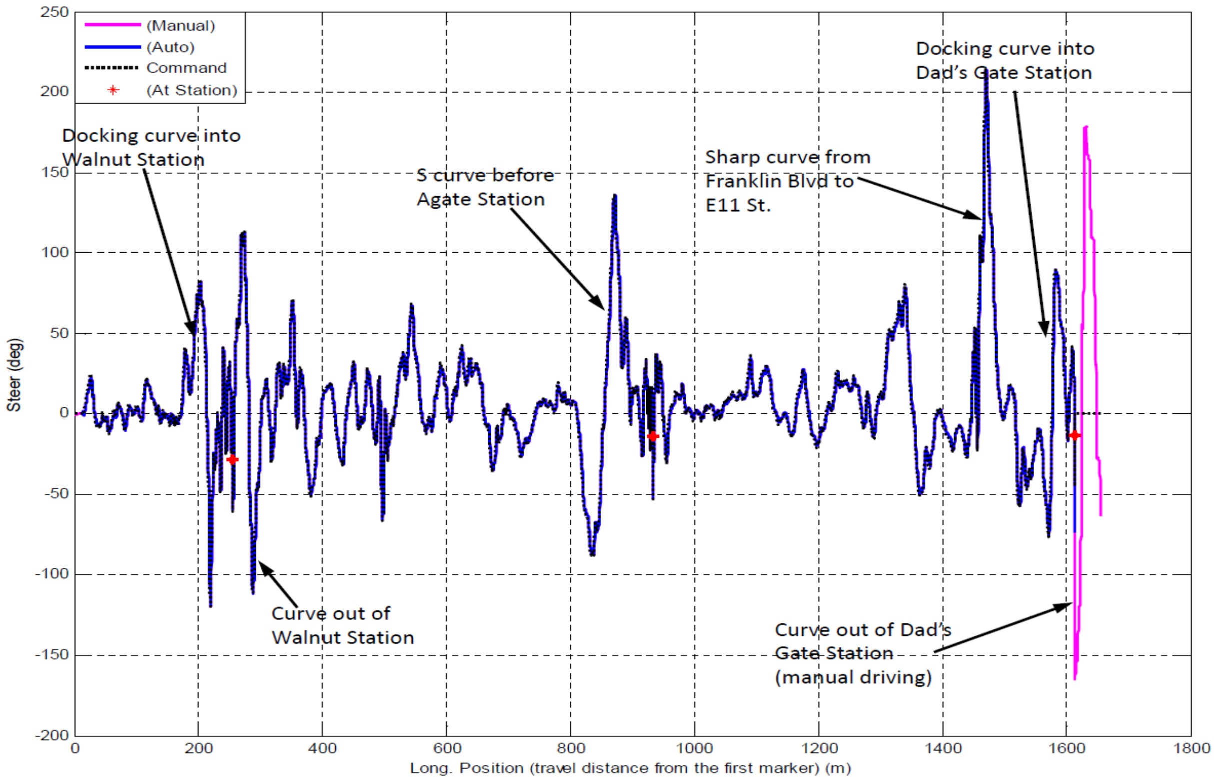


Figure 5-34 EmX WB run: steering angle and command of the steering wheel (distance based)

Similar to Figure 5-31, Figure 5-35 shows the time traces of the lateral position, vehicle speed, LED lights, and switch for the selected east-bound run. Similar to the west-bound run, the VAA system became transition ready at about 0.4 seconds after the first magnet was detected. The driver switched to "auto" 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 creped forward to finally stop at the desired stop location[19]. The amber LED blinked as the bus reached the desired stop location. 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 Blvd. at around 225 seconds. After a 17-second stop, the bus made the sharp right turn onto Franklin Blvd. and came to a stop again for the traffic light at Onyx St. At 293 seconds, the bus went through the Onyx 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 St. and Walnut St., and then it arrived at Walnut Station at 453 seconds. Similarly, 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

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

automatic system was disengaged but the system could still transit 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 east-bound 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[20] 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 is 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.

Figure 5-38 and Figure 5-37 show the lateral position, vehicle speed, and vehicle heading angle with respect to the distance traveled from the first magnet for the east-bound run. As shown in Figure 5-37, the vehicle angle was within 2 degrees 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 Ave. to Franklin Blvd., the docking curve into Agate Station, and the docking curve into Walnut Station. Similar to the west-bound run, the vehicle angle quickly converged to be smaller than 0.1 degrees once the bus completed the docking curve and stopped at the stations, indicating the bus was almost parallel to the platform.

Figure 5-38 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 5-36) and vehicle angle (Figure 5-37), at the transition between the manual driving and the automatic control indicates smooth transitions. The steering angle on the EmX Route was in general less than 100 degrees. The steering angle reached its maximum of 215 degrees on the docking curve into Agate Station (where the bus made more than two lane changes within 223 feet). Large steering angles over 150 degrees were also observed on the sharp right turn from E 11 Ave. to Franklin Blvd. and the docking curve into Walnut Station. These larger steering angles are the result of tightly following the magnet track.

[20] A position (or negative) lateral position indicate 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 the bus is closer to (or farther away from) the platform than the desired position.

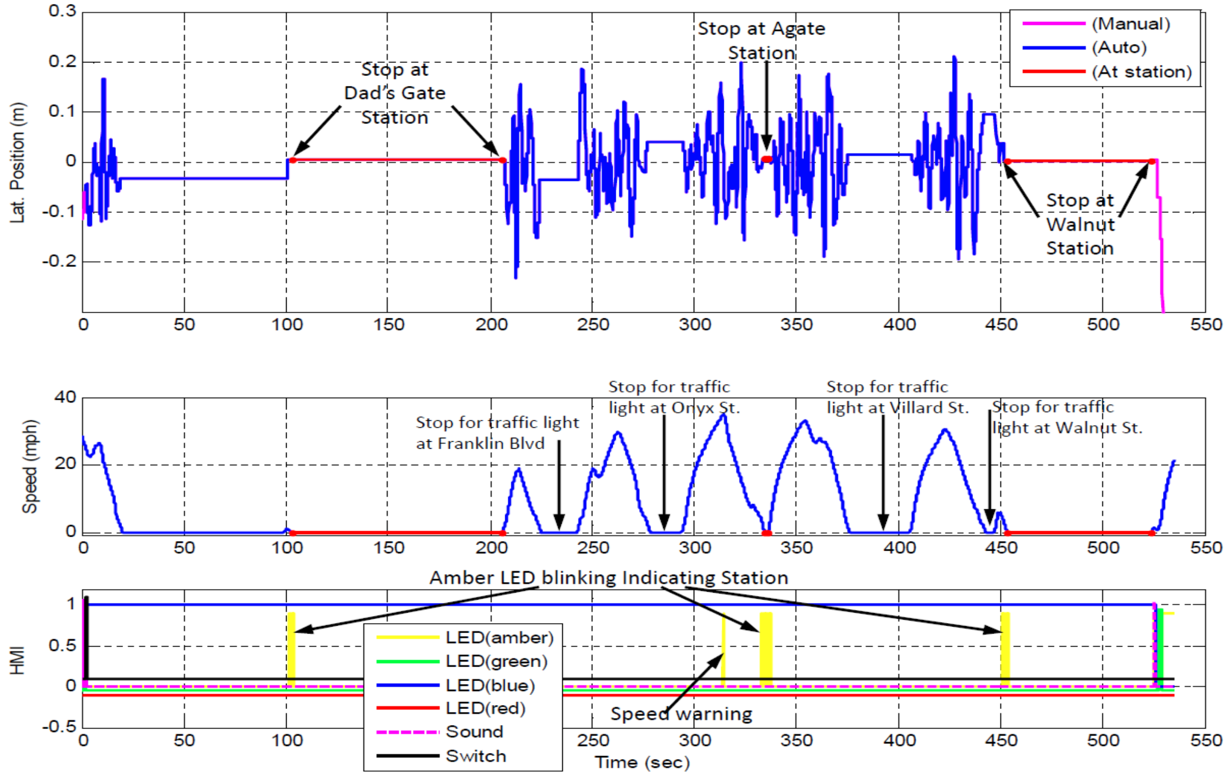


Figure 5-35 EmX EB run: lateral position error, speed, and HMI LEDs & switch (time based)

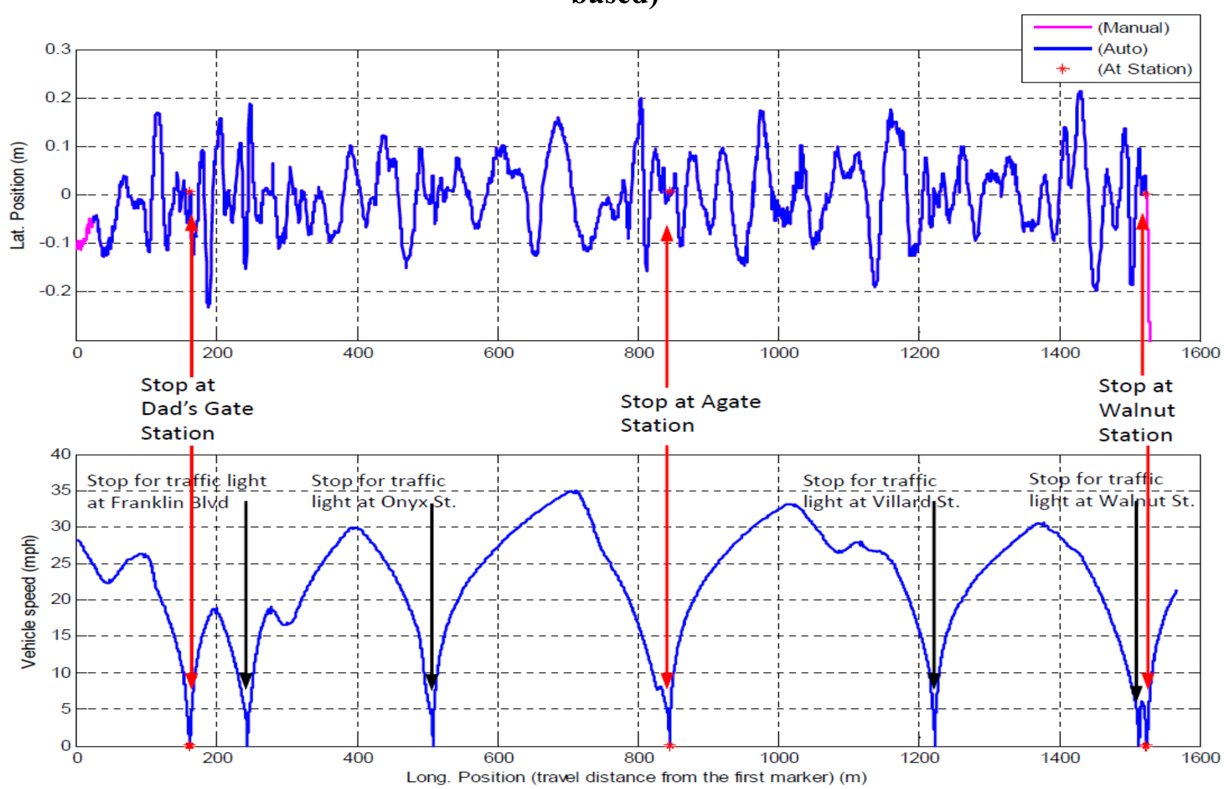


Figure 5-36 EmX EB run: lateral position error and speed (distance based)

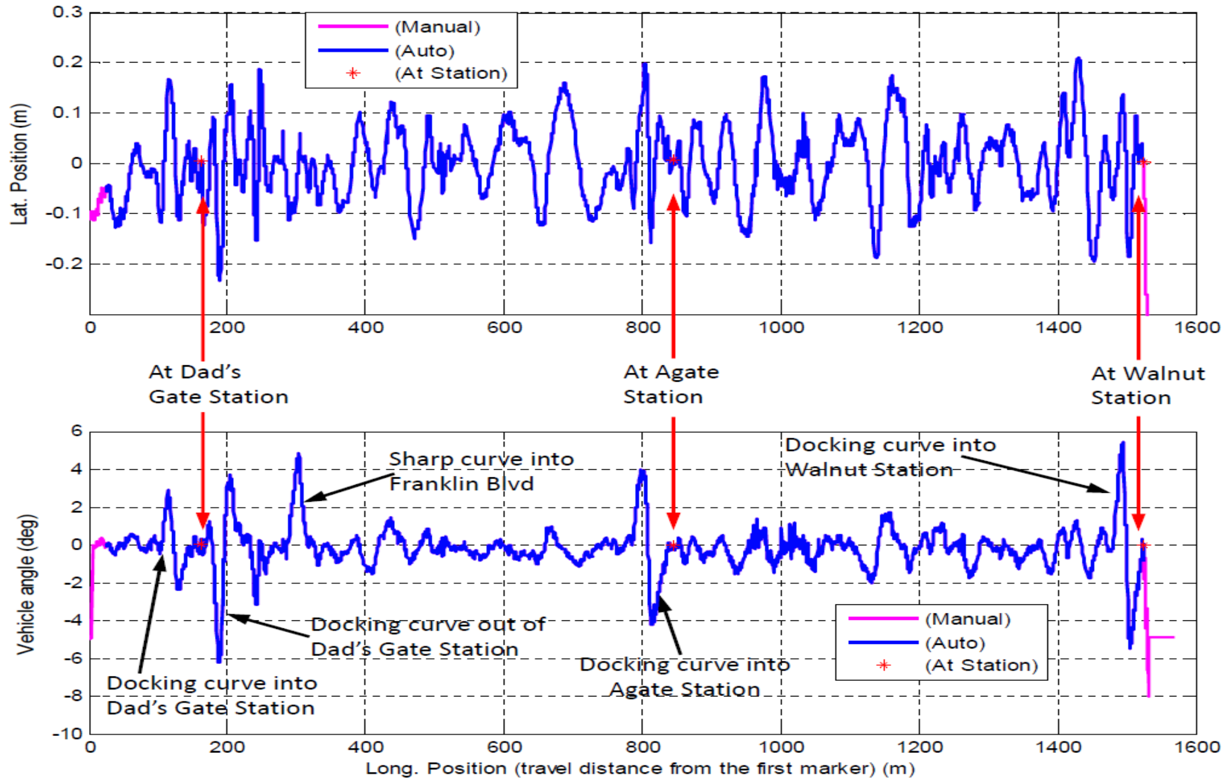


Figure 5-37 EmX EB run: lateral position error and vehicle angle (distance based)

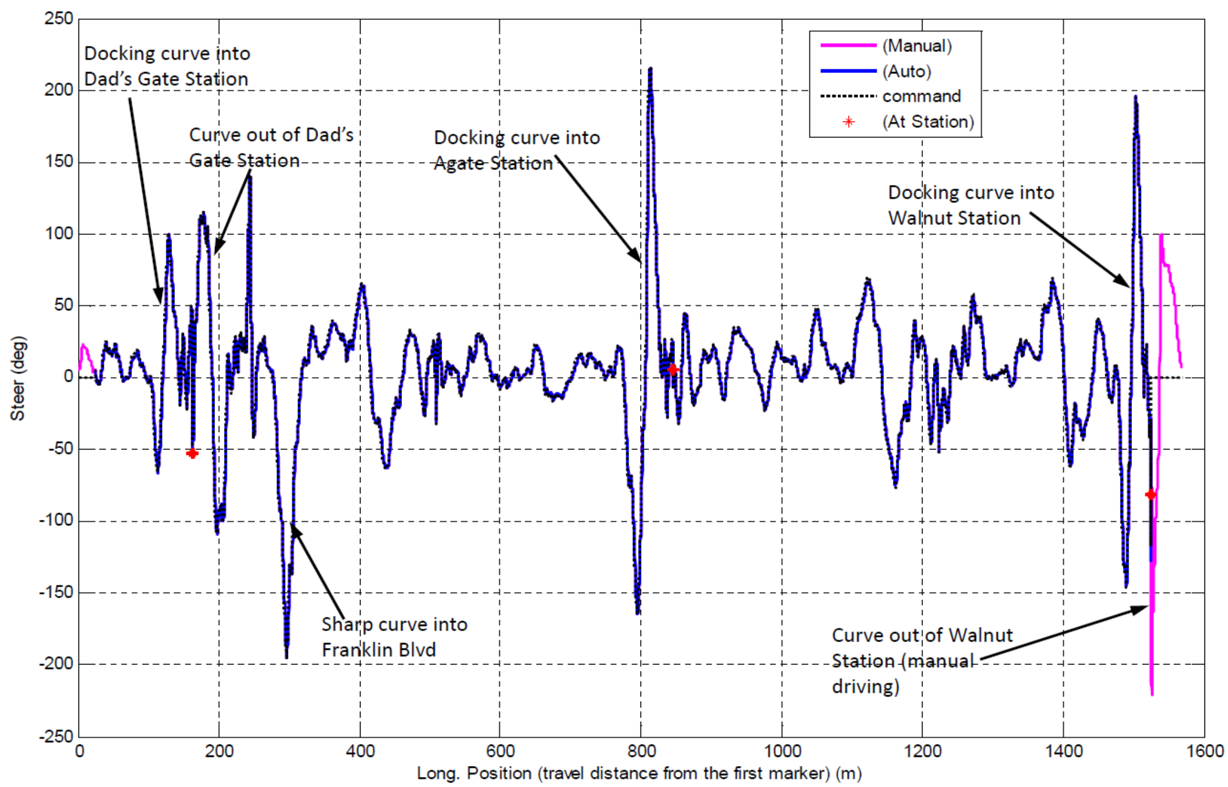


Figure 5-38 EmX EB run: steering angle and command of the steering wheel (distance based)

5.6 Operational Tests: Revenue Service Results

Upon successful completion of the field testing without passengers, VAA operations in revenue service started on June 10, 2013. After operating for almost five months, VAA operations in revenue service was suspended on Oct. 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 over 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 was in manual mode.

For the 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 drivers' and passengers' perception during the revenue service of the VAA system, and assessing the impact of the VAA technologies on maintenance.

5.6.1 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 5-39 shows the position error, speed, and steering wheel angle of one west-bound revenue service run with respect to the travel distance from the beginning of the magnet track. The steering angle reached its maximum of 213 degrees during the sharp turn (35 m radius) from Franklin Blvd. to E 11 Ave. 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 20cm except on the sharp docking curve leading to Dad's Gate Station.

Figure 5-40 shows the position error, speed, and steering wheel angle of one east-bound 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 shows the data for west-bound 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 where 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.

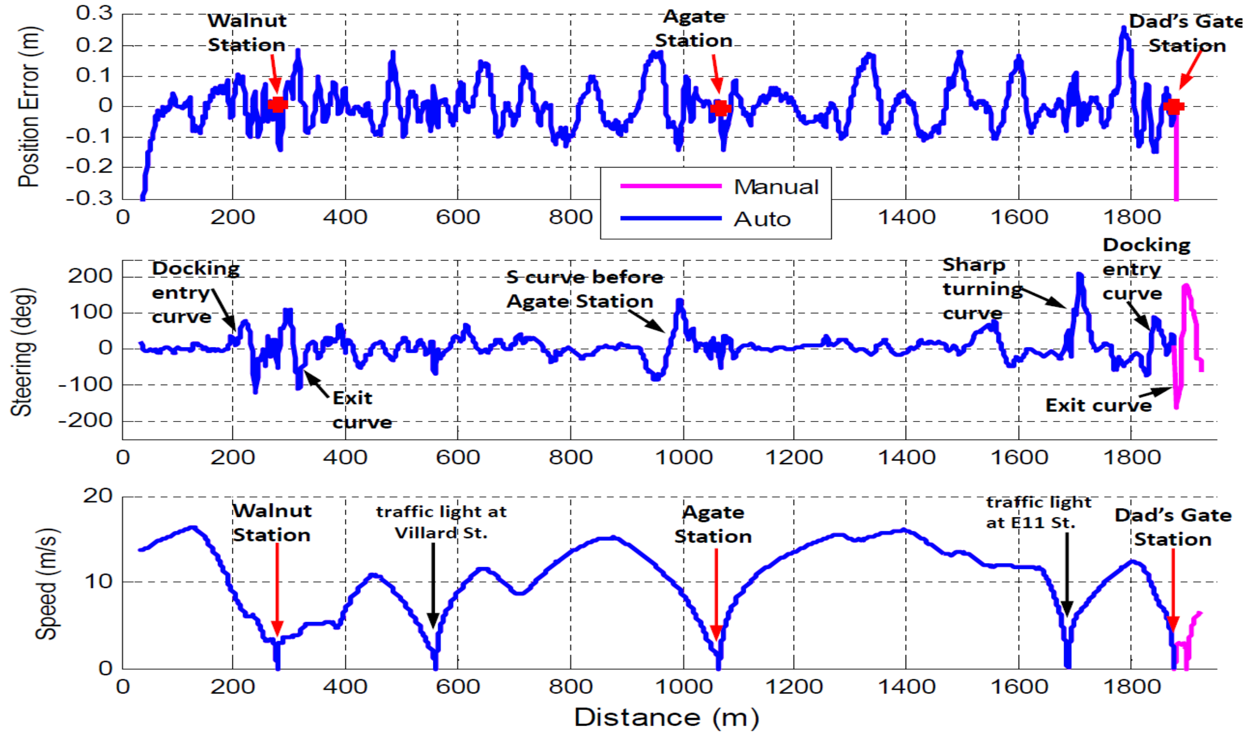


Figure 5-39 EmX WB revenue service run: lateral position error, steering wheel angle, and speed (distance based)

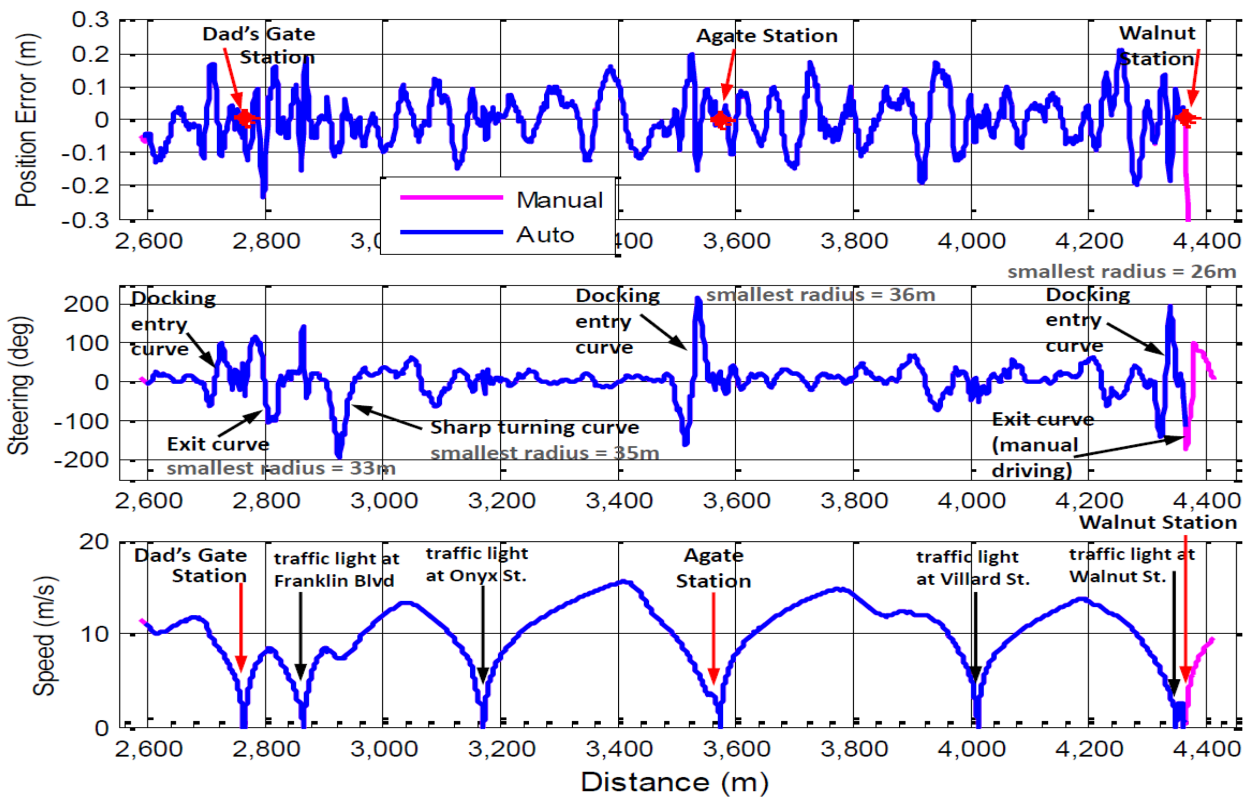


Figure 5-40 EmX EB revenue service run: lateral position error, steering wheel angle, and speed (distance based)

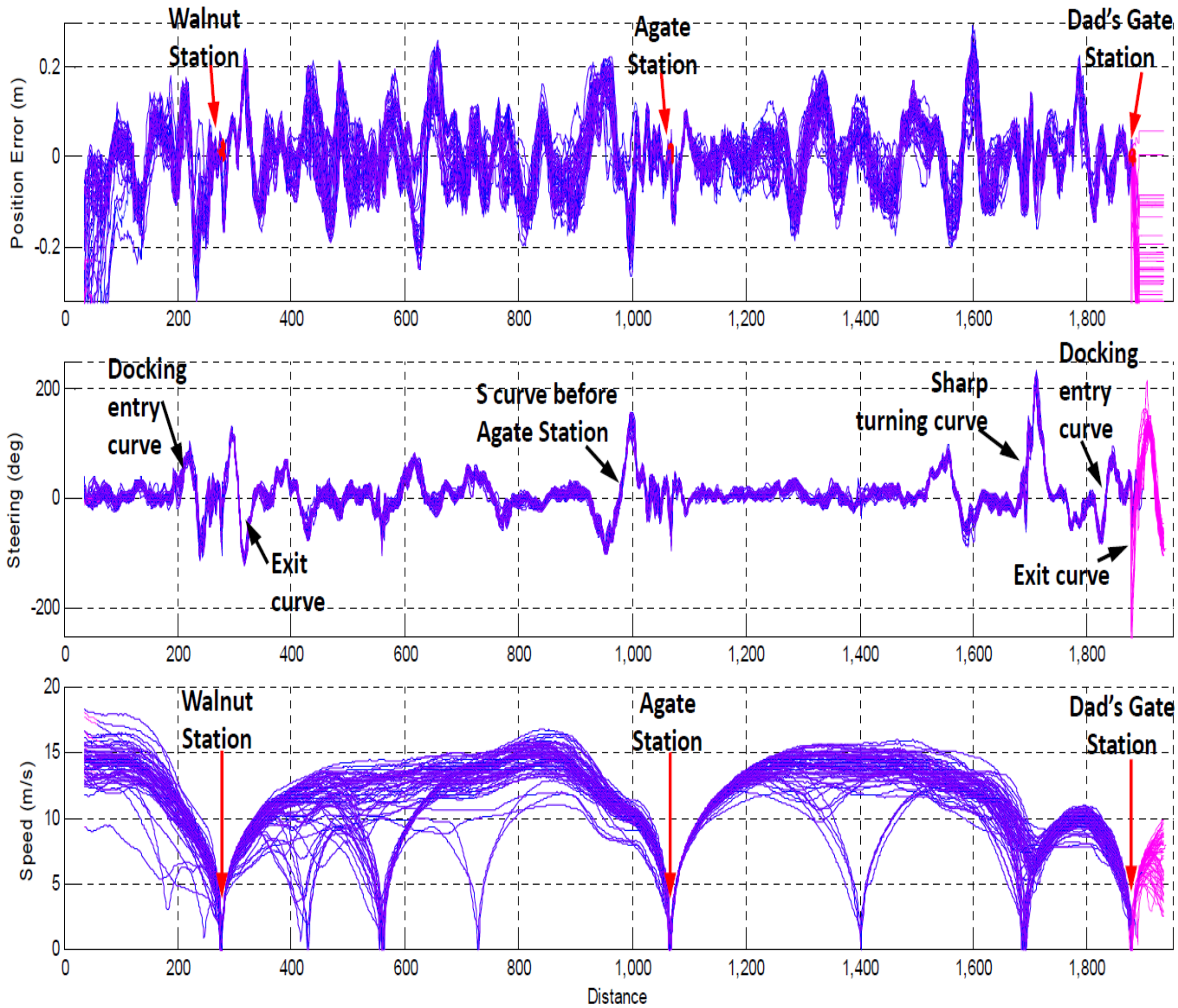


Figure 5-41 EmX WB revenue service runs in July 2013: lateral position error, steering wheel angle, and vehicle speed (distance based)

Precision docking was performed at six locations (three stations in each direction). The target horizontal gap for precision docking is 4 cm between the vehicle and platform edge. Our measurements at stations indicated that the horizontal gap was usually between 3 cm and 5 cm at both the front and the rear tire locations at all three stations. Data from revenue service confirmed that the position errors were almost all within $\pm$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 5-42 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 drivers' speeds. Drivers entered the docking curve at speeds as high as 40 km/h and reached the platform at 24 km/h (see the bottom left subplot). The control system performed steering corrections to pull the bus straight at the platform (see that both position errors go to 0). In addition, as the bus was pulling straight at the station, the steering angle exhibited larger variations (see circled areas), demonstrating the effects of the controller's ability to avoid hitting the platform while achieving the consistently tight docking gap. It's worthwhile noting that the bus/tires never touched the platform/strip or curb during the entire revenue service.

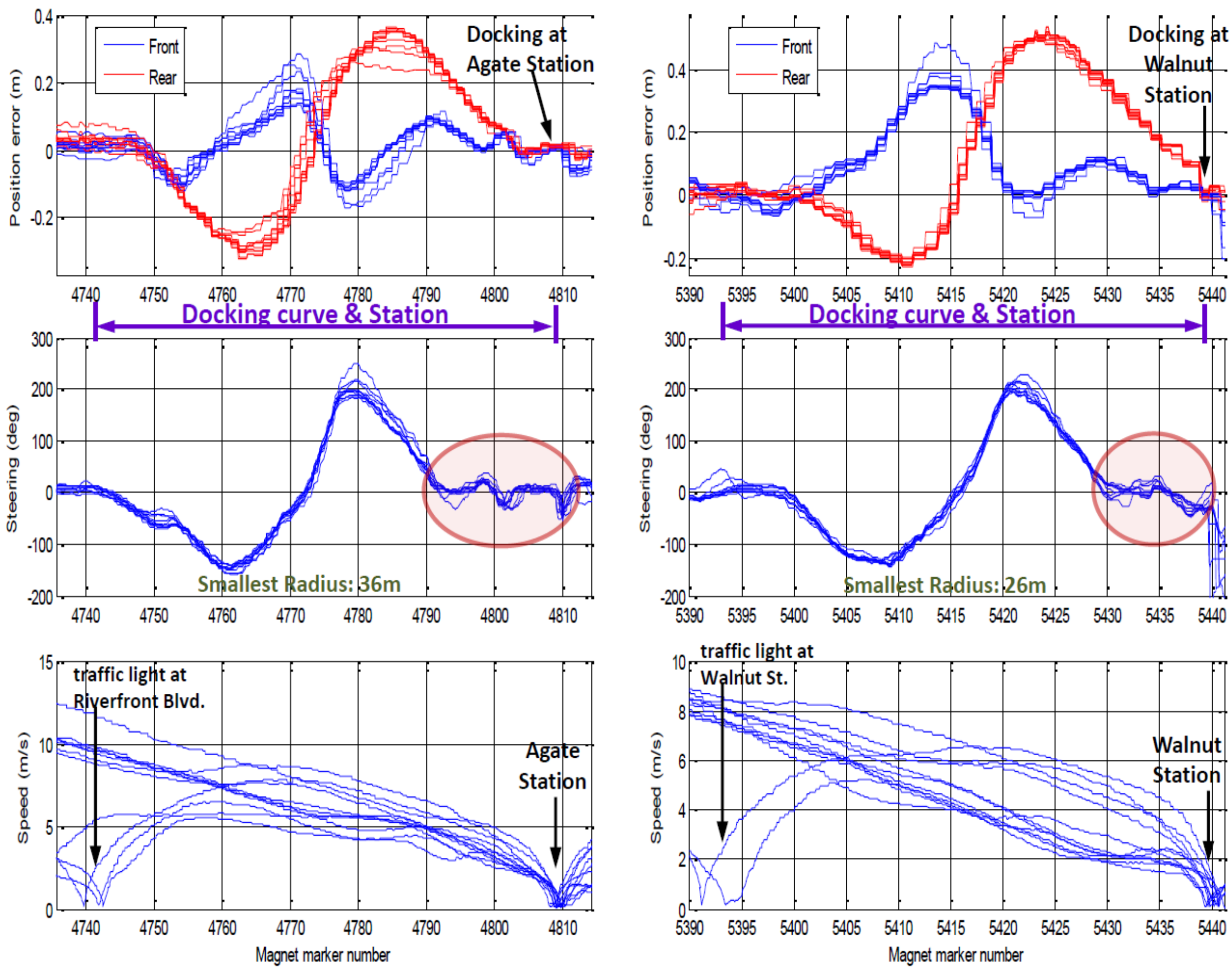


Figure 5-42 Docking performance at EB Agate Station (left) and EB Walnut Station (right) (One day's of revenue service data)

There is one comment of the lane keeping performance that 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. In order 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 is under the required lateral standard deviation target (7.6 cm).

5.6.2 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 5-43 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 are noticeably smaller and more consistent than those under manual steering[21]. The STD for the automatic steering is 7.15 cm while the STD for the manual steering is 16.81 cm. In addition, manual and automated driving generated the same level of the lateral accelerations.

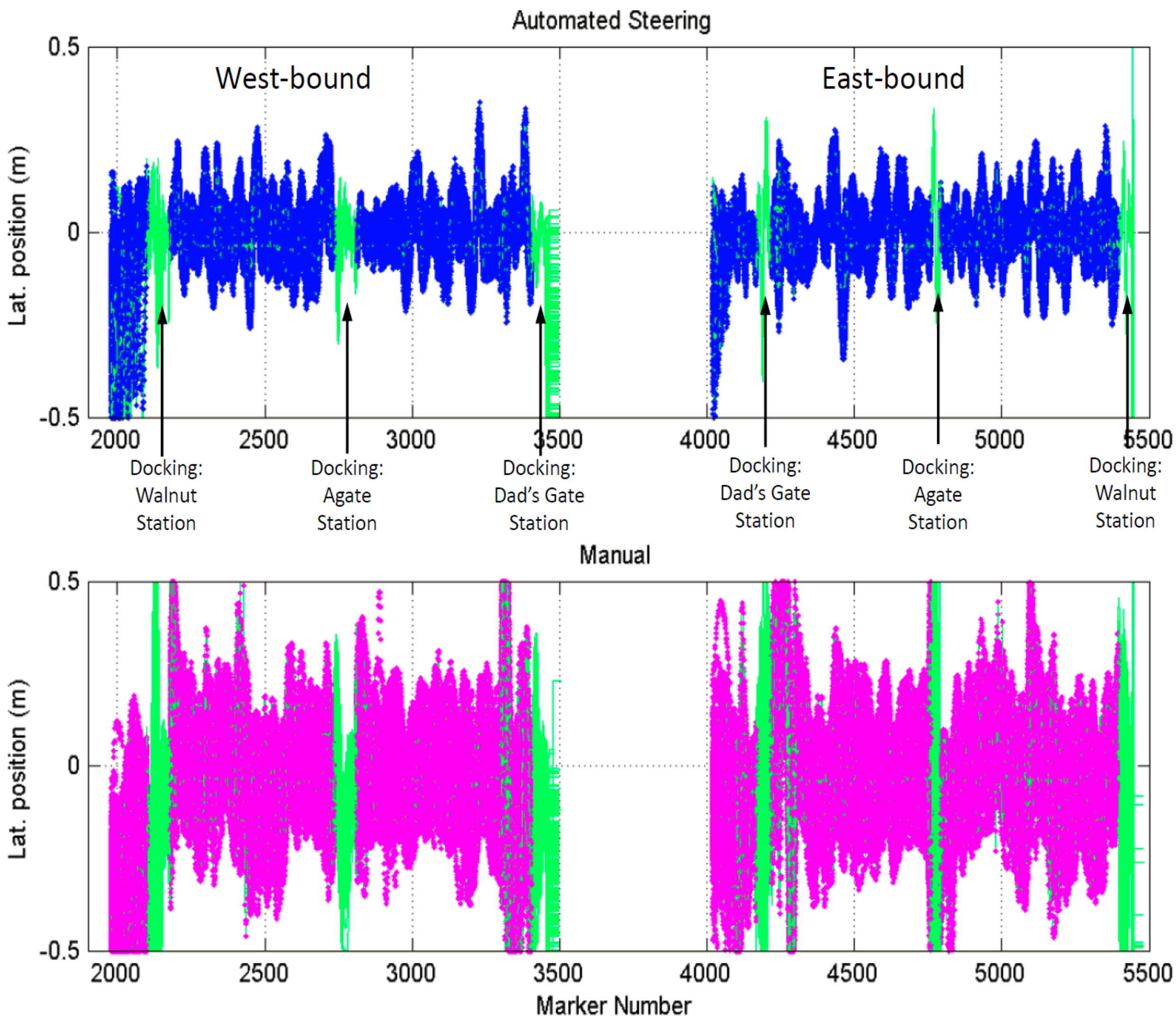


Figure 5-43 Comparison of lateral positions: automated (upper plot) vs. manual driving (bottom plot)

Figure 5-44 shows the speed and steering wheel angle under revenue service operations. The blue lines and the magenta lines correspond to the automatic steering control and the manual

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

steering, respectively. In general, the vehicle speeds under automation are compatible with those under manual driving, with manual steering achieving maximum speeds slightly higher (~1-1.5 m/s) than the automated steering.

The steering wheel angles in the bottom plot of Figure 5-44 show that the steering angles under automation are compatible with those under manual driving. Moreover, the steering angles under automation are more consistent than those under manual driving, especially on sharp curves, including docking curves. In addition, the steering angles exceeded 100 degree at over 20 locations under either manual or automatic steering; the maximum steering rate can reach over 300 degree/sec depending on the vehicle speed. These observations again reflect that this narrow corridor is indeed a challenging BRT route from the perspectives of performance and safety.

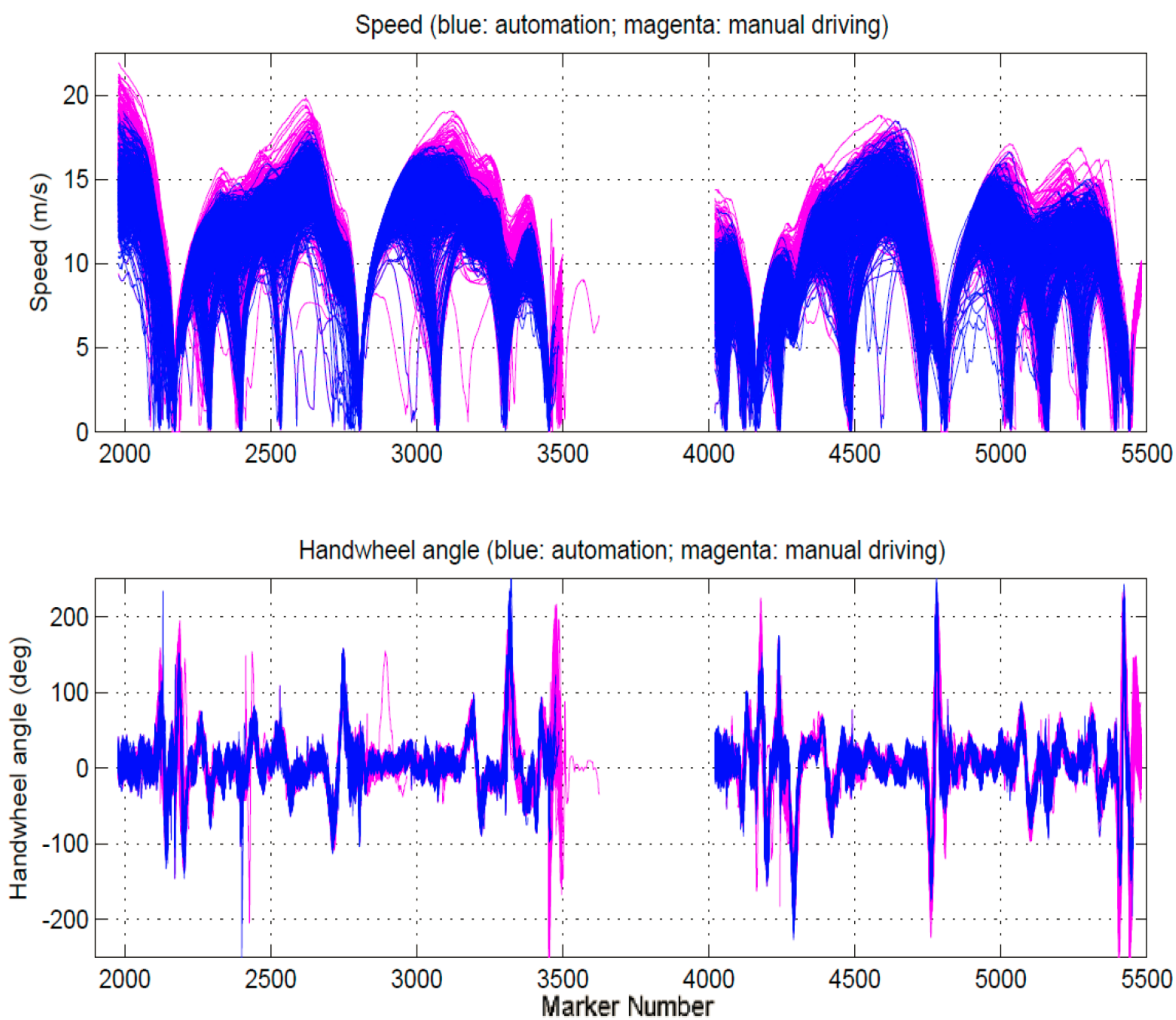


Figure 5-44 Revenue Service: bus speed (upper plot) and steering wheel angle (bottom plot)

5.6.3 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 so as 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, we present the statistical results based on data recorded during revenue service.

After every new driver bid process, some drivers who had not been trained for the VAA-equipped bus would be assigned to the VAA bus operational slot. Thus the VAA driver training had to be repeated for these new drivers. During this period, those new drivers drove the VAA bus under the manual mode at his/her designated time slots before they were 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 happened throughout the entire VAA testing period. Thus, the data collected during revenue service include both the data when the bus was under automated steering and the data when the bus was under manual steering. Table 5-2 lists the number of runs under automated steering and manual steering for each month during the revenue service testing periods. Note that the VAA automated steering was disabled on Oct. 15, 2013 and did not resume until Fall 2014. Due to some 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	
	West-bound runs	East-bound runs	West-bound runs	East-bound runs
6/2013	70	71	106	104
7/2013	90	92	118	117
8/2013	62	61	131	130
9/2013	148	143	59	64
10/2013	78	84	113	108
11/2013	0	0	220	221
12/2013	0	0	222	222
9/2014	6	6	67	69
10/2014	85	84	134	133
11/2014	2	5	218	215
12/2014	0	0	56	56

5.6.4 Operational improvements

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

Figure 5-45 shows the standard deviation of the lane keeping lateral deviation for each month during VAA revenue service operations. In the months where automated steering data were available, the lane-keeping lateral deviation achieved by automated steering has a standard deviation less than half of that achieved under manual steering. Also as shown in Figure 5-45, the monthly standard deviations of the lane keeping lateral deviation are between 6.07 cm and 7.68 cm for automated steering, while the monthly standard deviations of the lane keeping lateral deviation are between 14.79 cm and 16.84 cm for manual steering. The advantage of the automated steering is evident.

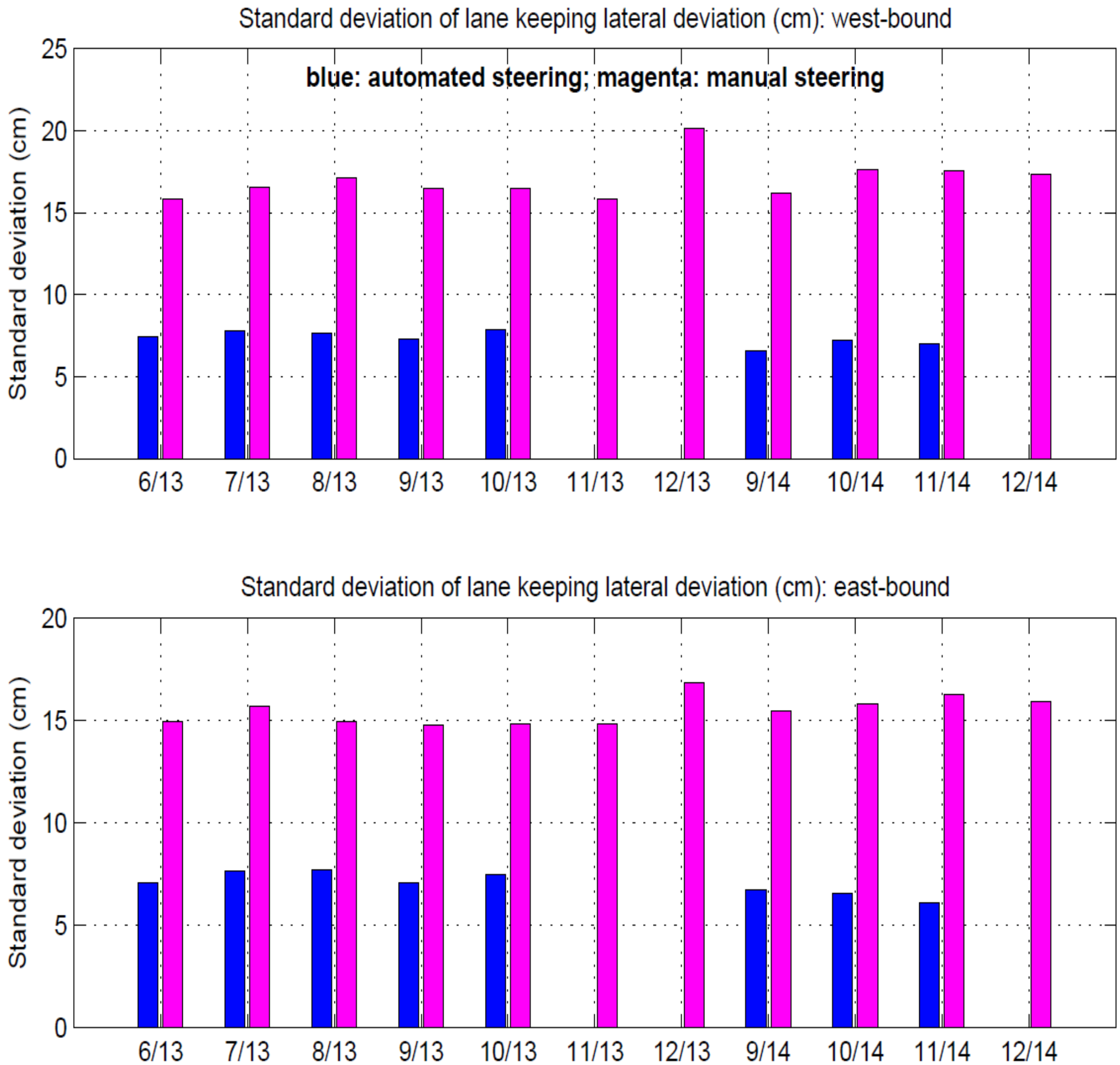
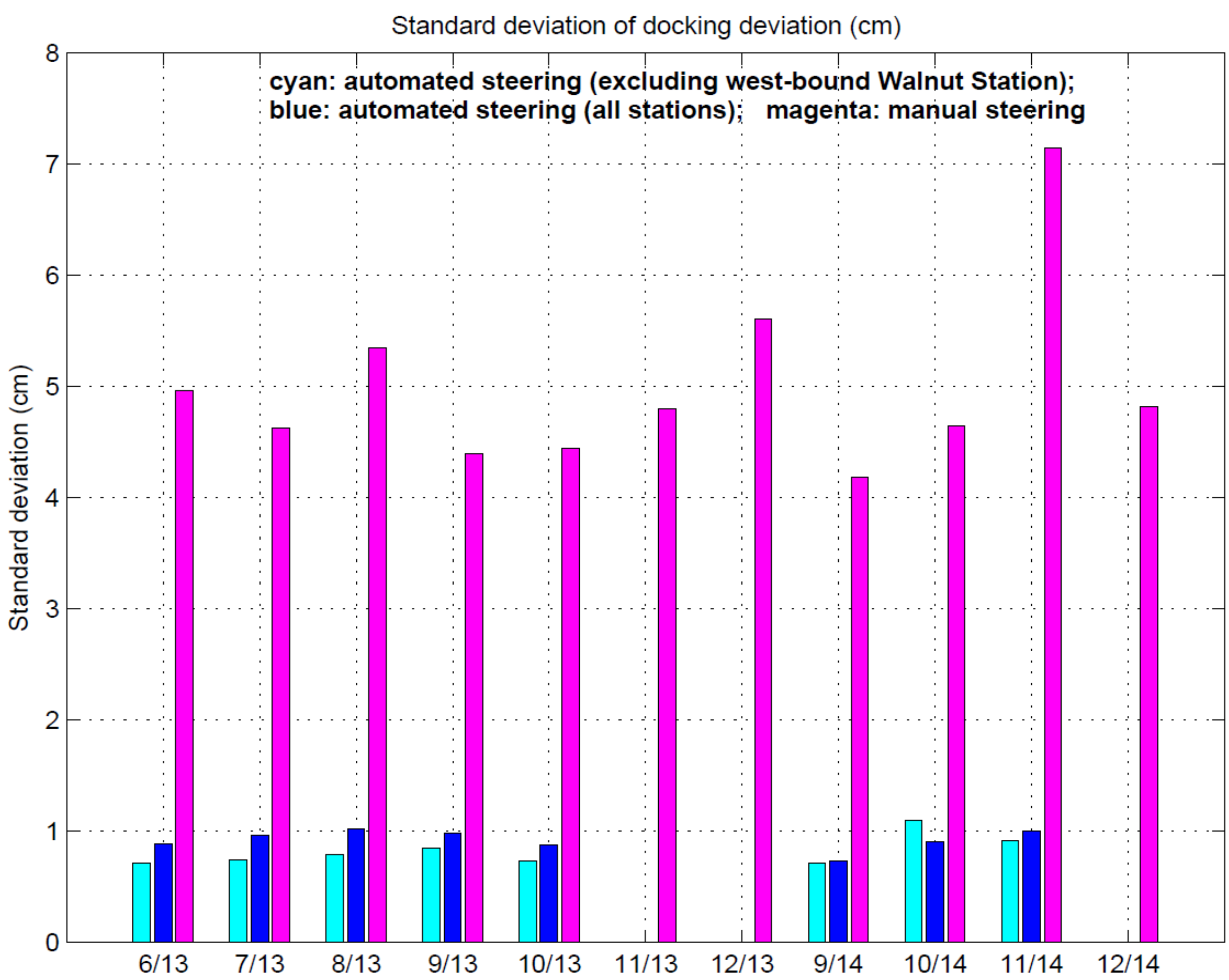


Figure 5-45 Standard deviation of lane keeping deviation for each month of revenue service (blue: automated steering, magenta: manual steering)

Figure 5-46 shows the standard deviation of the precision docking errors for each month during revenue service. The standard deviations 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 standard deviations 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 west-bound Walnut Station[22] is excluded, the standard deviations (shown as cyan bars) under automated steering ranges from 0.71 cm to 0.85 cm except in Oct. 2014 and Nov. 2014. During an investigation at the end of Oct. 2014, it turned out 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 tailed 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. And finally in Nov. 2014, due to some administration reasons, there were only two west-bound runs and 5 east-bound runs that were conducted under automated steering. Thus, the precision docking data in Nov. 2014 may not be statistically significant to represent the docking performance.



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

Figure 5-46 Standard deviation of docking deviation for each month of revenue service (cyan: automated steering (excluding the west-bound Walnut Station), blue: automated steering (all stations), and magenta: manual steering (all stations)).

Figure 5-47 compares the standard deviation of the lateral accelerations (measured inside the instrument cabinet behind the front tire) under the automated steering and that under the manual driving for each month. The automated steering achieved standard deviations slightly smaller than the manual steering. This comparison indicates that the automated steering provides a slight advance in ride comfort to the passengers as well.

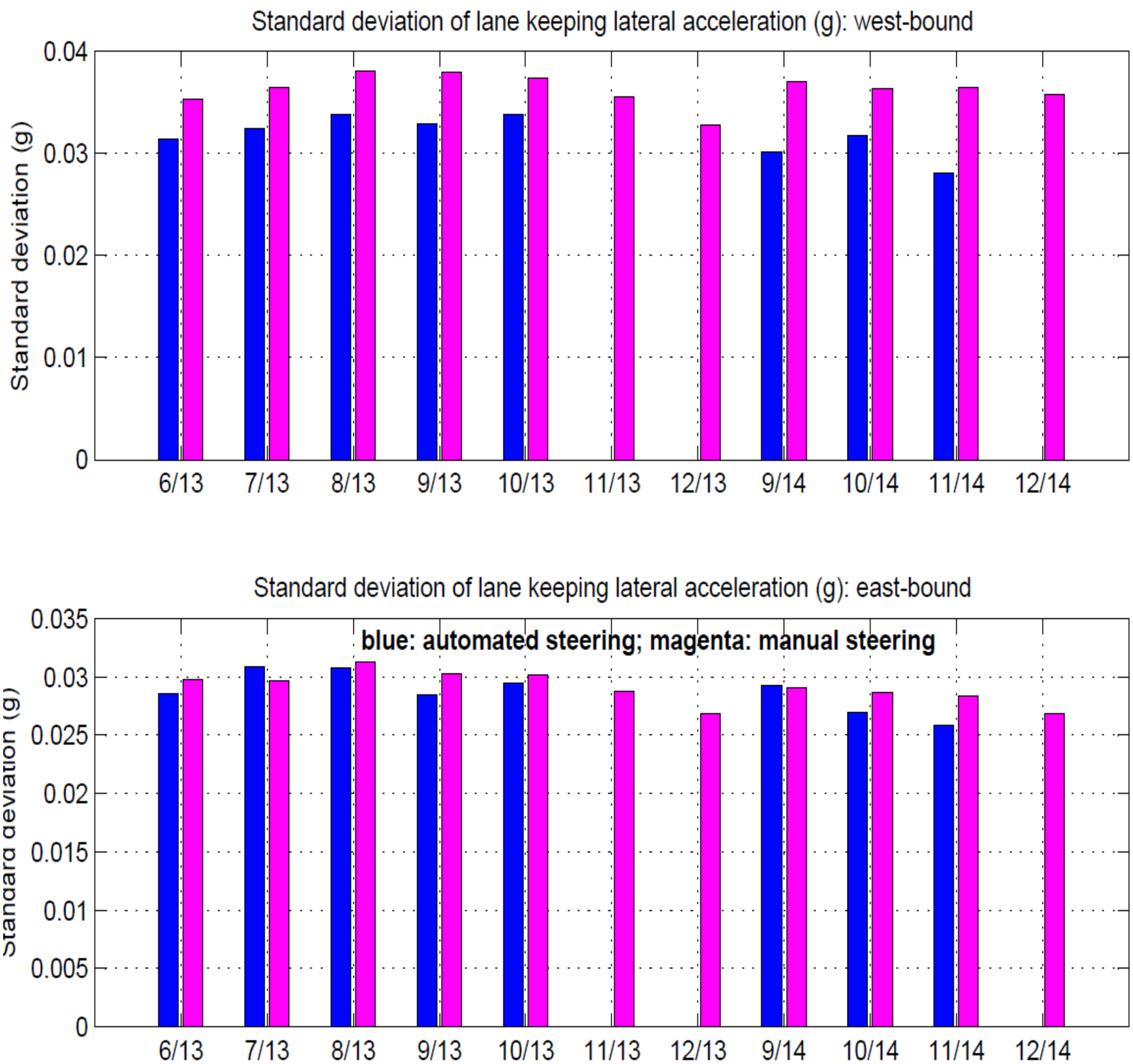


Figure 5-47 Standard deviation of lane keeping lateral acceleration (g)

To evaluate how automated steering would affect operating speed, the EmX route was segmented so as to compute the 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.

5.6.5 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 warmed the operator accordingly. On June 25, 2013, the VAA system detected faults in CAN communications and magnetic sensor bars twice. The first time the bus was under manual steering; the VAA system lit the red LED light on the HMI as an indication. The second time it happened, the bus was in automated steering mode and the VAA system provided an audible warning to the operator right away. The operator then took over the control and the transition was smooth. LTD identified that the cause was a bad alternator and it replaced the alternator subsequently. 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 as well and the battery failed as a result. Those incidences demonstrated that the VAA system itself was reliable and that system fault detection and management functioned correctly.

The VAA system generated one false alarm per month on average. 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.

6.0 Lessons Learned and Recommendations

This chapter presents the lessons that were learned through the lifecycle of the VAA Demonstration project. It also provides recommendations based on those lessons.

6.1 Lessons Learned

The VAA project was one of the first vehicle automation and assist projects in the U.S. that dealt with many real-world deployment issues. Those issues included: (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, 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.

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 is "is the system safe?" The answer to this question 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 the active safety systems or automated systems in a vehicle is still a new area in vehicle applications and as such, a 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 all essential for developing and deploying such a safety-critical system at the current state of vehicle automation. A complimentary team would need to be formed in order to leverage the knowledge and experience of each individual's expertise 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 the development, it was determined that fault detection and warning are essential to safe operations. Another discovery was to design a degraded-mode control which 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; but 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 back 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 reason the only safety related incident that occurred during the entire VAA testing and revenue service period was the combination of two events: 1) a control computer failed, and 2) 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 therefore 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 the 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 the track layout, road geometry, possible range of measurement noises, operational speeds, and the controller robustness.

Developing the VAA system for LTD was a learning process that leveraged the control technologies and the experiences of the transit operators. While 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, while 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 a 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 their speed control with their steering action. They anticipate and prepare controlling the bus's speed based on their steering actions. Compared to the way a driver controls the bus, which is to look forward towards the horizon, the VAA automatic steering control system looks down at the trail of magnets embedded in the roadway. This means that the 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, the 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 they 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 stage of development and deployment, it is the developer's role to ensure system safety and to educate the transit agency about safe operations.

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

The lateral acceleration data showed that most passengers would not feel the difference between having the VAA system enabled and disabled. However the 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. Below 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 this particular driver's left knee often touched the emergency button during the docking maneuver. The solution was to add a protective plate next to the emergency button to prevent such occurrences from occurring in the future.

- The VAA system detected several intermittent faults during VAA operations (a couple of times a day) in July 2013. The system provided warnings and maintained degraded-mode control during this time frame. After the warnings were discovered, causes were found through analysis of the data to be various power supply problems from the bus itself. First it was intermittent low voltage levels to the VAA sensors due to an alternator failure and a bad battery. Then the replacement alternator had a diode failure that created power glitches to the VAA system. Finally a video system damaged by the power failure created power fluctuation that impacted part of the VAA system which connected to the same power terminal. All of these discoveries led to better maintenance inspections of the bus as well as future recommendations of looking at how power is supplied and possibly 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 westbound Walnut Station. The data indicated that the bus did have an additional 2 cm lateral movement toward the curb due to an unknown reason, yet that 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 which revealed that there was a 5 cm discrepancy between the surveyed data and the true locations with respect to the magnets. The 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. It was discovered that risk management across the board was important, from contracts, liability, safety, technologies, resources, team availability, equipment, and various support. Any one of these items could and often did cause delays in the project delivery. While it is critical to have well thought out project planning and design from at the start of the project, it is not practical at the proposal stage to anticipate and plan for every real-world issues, including major institutional and contractual complications. As a result the project experienced significant delays and challenges that were beyond the predictions of the project team. The VAA project already consisted of a complex system and added in a complex working environment consisting of two states, multiple cities (and local jurisdictions), two transit agencies, the University of California, Berkeley, Caltrans, and various subcontractors.

Due to safety critical nature of VAA system, the contractual arrangements between the university and the contracting partners became much more complicated than typical research contracts and caused substantial delays. Among all subcontracts, the original SOW and proposal calls for a steering actuator supplier to develop a modified electric power steering actuator. However, because the difficulties for the university to accept supplier's conditions on liability, the contract negotiation was stalled. As the steering actuator is a critical component for the VAA system, the project team had to design the steering actuator with the support of another vendor. Both the unanticipated contract negotiation and the time needed for the design caused the longest delay and also the largest schedule implications. Also due to liability issues, the contract with the two transit agencies were also delayed.

Finally, the VAA project experienced its longest delay of one year due to a Caltrans internal review that added additional requirements to the contract between Caltrans and the University. During this one-year delay, the VAA project (including LTD revenue service operations) was suspended. By the time the contractual issue was resolved between the University and Caltrans in September 2013, the VAA project had about five months left and the subcontracts to the transit agencies also needed some modifications. Eventually, the subcontract with the LTD was renewed and the revenue service started again in October 2014. The modification of the AC Transit contract did not have sufficient time to execute although the VAA system was basically ready for highway testing just before the suspension in 2013.

In addition to delays caused by the contractual and liability complications, other technical and maintenance issues were also encountered. Around the end of 2011, several maintenance issues of the testing buses caused additional delays. Most of these delays were beyond the control of the project team and everybody did their best to minimize the schedule impacts. 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 United States.

Lessons learned include an effective risk management plan is critical to continuously identify and address the issues as they appeared in the areas of safety, performance, costs, resources, operations, and contracting before they impacted delivery. Frequent and regular communications was found to be 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.

6.2 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. First, there must be a need for deploying a specific VAA application. For example, LTD needed precision docking for their 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 which occurred occasionally during manual docking maneuvers. VAA was able to address this need. Second, 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. Third, the technology needs to be available and a team ready to deliver it. In this project, PATH had almost twenty years of practical experience in vehicle automation and control systems. Fourth, 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. They 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 addressed the safety issues specific to the automated system utilized in 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 comprised of electrical, electronic, and software components, and 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 the recommendation of the PATH development team that the current VAA system needs one more design and development iteration in order 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 at least 6 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 who wants to deploy their 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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8.0 Appendices

8.1 Appendix A: J1939 message list for New Flyer 60' Diesel articulated bus

A list of useful J1939 messages for VAA system is given below:

1. Electronic retarder controller #1

Electronic Retarder Controller #1	Unit	Range	Updating period
enable brake assist status	Status		100ms
actual retarder percent torque	Percent	-125 to +125	100ms

2. Electronic brake controller #1

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

3. Electronic transmission controller #1

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

4. Electronic engine controller #1

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

5. Electronic engine controller #2

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

6. Electronic transmission controller #2

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

7. Electronic engine controller #3

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

8. Retarder configuration

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

9. Engine configuration

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

10. Electronic brake controller #2

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

8.2 Appendix B: Component Test Results

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

Steering Actuator Test Results

The table below lists the features tested, the test procedure for conducting the specific test cases, as well as the corresponding acceptance criteria according to the component test plan for the steering actuator. The test results are listed in the right column, which show that the steering actuator passed all the acceptance criteria in the table.

Features	**Test Procedure**	**Acceptance Criteria**	**Test Results**
Steering actuator sensor range, resolution, and accuracy	Command the steering actuator motor such that the steering wheel travels its whole range, record the measurements of the angular position sensor, and examine the measurements against the 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 the encoder and the potentiometer measure the full range of the steering wheel travel (-825 degree to 825 degree). The resolution of the encoder is smaller than 0.2 degree and the resolution for the potentiometer is 1 degree.
Steering actuator torque capacity	Measure the steering torque applied to the steering column; examine the measurements against the motor specifications.	The steering actuator shall be able to provide torque to the steering column and the torque capacity shall meet the specifications.	Passed. The steering actuator embedded processor provides a torque command to the steering actuator motor, and the maximum torque capacity meets the specifications.

Features	Test Procedure	Acceptance Criteria	Test Results
Steering actuator mechanical design	Examine the mechanical design of the actuator assembly to ensure that no modification has been made to the steering column.	The steering actuator assembly shall not reduce the mechanical property (e.g., the strength) of the original steering column.	Passed. There is no modification to the existing steering column; thus the steering actuator assembly would not reduce the mechanical property of the original steering column.
Steering actuator mechanical space	Measure the mechanical space of the steering actuator and compare it with the available space in the bus; further install the steering actuator into the test bus and examine the 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 the steering actuator motor so as to extensively test the steering actuator assembly; examine whether any backlash has been developed or any vibration occurs, if so, measure the size of the backlash as well as the frequency of the vibrations.	The steering actuator assembly shall not have excessive backlash or gap that generates vibrations of the assembly.	Passed.
Steering actuator embedded processor	Test the processor with the data exchange rate (on the interface) up to at least 5 times of that in the normal operation and the computation cycle reduced to at least 1/5th of that in the normal operation to evaluate the 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. The embedded processor shows consistently reliable performance with the data exchange rate (on the interface) at 5 times of that in the normal operation and the computation cycle reduced to 1/5th of that in the normal operation.

Features	Test Procedure	Acceptance Criteria	Test Results
Steering actuator embedded processor interface	Connect the steering actuator embedded processor to the steering actuator motor's Electronic Control Unit (ECU) and the control computer; and verify the data exchanges through the 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 the steering actuator motor and the embedded processor can operate with the power from the 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 the steering actuator into the bus, connect the steering actuator embedded processor to the steering actuator motor's ECU (now in the bus) and the control computer in the bus, verify the interface, command the motor ECU to steer the steering wheel with various steering commands, and monitor/examine the operation.	The embedded processor shall work in the bus/vehicle environment (electronically, mechanically, and environmentally).	Passed
Steering actuator embedded processor mechanical design	Repeated install and uninstall the embedded processor, as well as connect it to and disconnect it from the steering actuator assembly and the control computer, evaluate the 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 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 as well as inconsistency between the measurements from the motor encoder and those from the potentiometer. The resolutions included initializing the software drivers for the sensors and modifying the reading frequency of the motor encoder.

Magnetic Sensor Module Test Results

The table below lists the features tested, the test procedure for conducting the specific test cases, as well as the corresponding acceptance criteria according to the component test plan for the magnetic sensor module. The test results are listed in the right column, which show that the magnetic sensor module passed all the acceptance criteria in the table.

Features	**Test Procedure**	**Acceptance Criteria**	**Test Results**
Magnetic sensor module sensing range, resolution, and accuracy	Place a magnet at various locations within the specified range, record the magnetic sensor measurements, measure and record the actual position of the magnet, compare the sensor measurements against the actual positions of the magnet to evaluate the sensor range, resolution, accuracy, as well as the 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. The total sensor range for the sensor module is +/- 1.05 meter and the resolution is 1mm. The sampling frequency of the sensor is above 250Hz.
Magnetic sensor module consistency	Select a few fixed locations, place a magnet at the fixed locations several times and record the sensor measurements, compare the sensor measurements corresponding to the same fixed locations to analysis the consistency of the measurements.	The magnetic sensor module shall provide consistent field measurements under environmental conditions specified in the specifications.	Passed. The consistency of the measurement for any fixed location is within 5mm.

Features	Test Procedure	Acceptance Criteria	Test Results
Magnetic sensor module mechanical design	Test the sensor module with water for its waterproofness, subject the sensor module to moderate oscillations and impacts that are severer than those typical during the normal operation of the bus and examine their effects on the 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 the magnetic sensor module assembly at a few selected locations under the test bus and evaluate the sensor module's distance to the side of the bus and its distance to the ground.	The magnetic sensor module assembly shall fit the limited spaces available under the bus frame.	Passed.
Magnetic sensor module embedded processor	Operate the embedded processor with the data exchange rate up to 3 times of that in the normal operation and the computation cycle reduced to at least $1/3^{rd}$ of that in the normal operation to evaluate the 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.
Magnetic sensor module embedded processor interface	Connect the sensor module embedded processor to the control computer; and evaluate the data exchange through the interface (e.g., no missing messages and 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. The embedded processor can communicate to the control computer at 50-100hz.
Magnetic sensor module power	After installing the magnetic sensor module assembly under the test bus; connect sensor module embedded processor to the power from the bus; verify the sensor module can operates with the power supply.	The magnetic sensors and the embedded processor shall satisfy the power specification for operating in the VAA bus.	Passed.

Features	Test Procedure	Acceptance Criteria	Test Results
Magnetic sensor module embedded processor environmental	After installing the magnetic sensor module assembly under the test bus and connecting it to the control computer and power, verify the operation of the embedded processor in the bus environment by driving the bus along a magnetic track, collecting the sensor measurements, and evaluating the sensor measurements.	The embedded processor shall work in the bus/vehicle environment (electronically, mechanically, and environmentally).	Passed. The sensor module was installed on a New Flyer bus and tested on a magnetic track at Richmond Field Station.
Magnetic sensor module calibration	After installing and interfacing the magnetic sensor module, place a magnet at various locations within the specified range, record the magnetic sensor measurements, measure and record the actual position of the magnet, and compare the sensor measurements against the actual positions of the magnet to evaluate the sensor calibration.	The magnetic sensor module shall be properly calibrated to remove/reduce errors due to the sensor installation misalignment.	Passed. The calibrated sensor module maintained the 5mm accuracy after installation.
Magnetic sensor module maintenance	Install and uninstall the magnetic sensor module, as well as connect it to and disconnect it from the control computer, and evaluate the 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. The installation and uninstallation procedure is straightforward and does 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, tightly coupled DGPS/INS integration system[23]. The module included a DGPS base station and a DGPS/INS mobile unit, which further consisted of one embedded computer, a dual-frequency GPS receiver, an Inertial Measurement Unit (IMU), a 900Mhz communication modem,

[23] 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.

a power module, as well as the associated antennae, software, and custom enclosure with cables and connectors.

The table below lists the features tested, the test procedure for conducting the specific test cases, as well as the corresponding acceptance criteria according to the component test plan for the DGPS/INS module. The test results are listed in the right column, which show that the DGPS/INS module passed all the acceptance criteria in the table.

Features	Test Procedure	Acceptance Criteria	Test Results
DGPS/INS module performance	Install the DGPS/INS module on a test vehicle and drive it around. Evaluate the position data collected and stored by the 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. The DGPS/INS mobile unit provides position with better than 5cm accuracy under ideal GPS conditions (with a clear view of the sky). The resolution is 1mm and the update rate is 30hz.
DGPS/INS module base station	Install the DGPS/INS module on a test vehicle and drive it around. Evaluate the reception of the differential signals from the 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 the DGPS/INS module on a test vehicle and drive it around a fix course and stop at several fix locations. Evaluate the accuracy of the position readings.	The DGPS/INS module shall be able to provide consistent position measurements under environmental conditions as described in the specifications.	Passed. The DGPS/INS module achieved better than 5mm accuracy consistently under ideal GPS conditions.
DGPS/INS module message content	Connect the GPS/INS module to the control computer; and evaluate the data exchange through the interface.	The DGPS/INS module shall provide at least the minimum message content as described in the component developer's SOW.	Passed. The DGPS/INS mobile unit provides real-time position coordinates, operational status, accuracy measures, confidence index, etc.

Features	Test Procedure	Acceptance Criteria	Test Results
DGPS/INS module mechanical design	Test the DGPS/INS module that is exposed to the bus external environment with water for its waterproofness, subject the module to moderate oscillations and impacts that are severer than those typical during the normal operation of the bus and examine their effects on the 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 the DGPS/INS module to the control computer; and evaluate the data exchange through the interface (e.g., no missing messages and 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. The DGPS/INS mobile unit can communicate with the control computer via either RS232 serial communication or Ethernet communication.
DGPS/INS module power	After installing the DGPS/INS module on the test bus, connect the module to the power from the bus, verify the module can operates with the power supply.	The DGPS/INS module shall satisfy the power specification for operating in the VAA bus.	Passed.
DGPS/INS module maintenance	Install and uninstall the DGPS/INS module, as well as connect it to and disconnect it from its control computer, and evaluate the 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. The installation and replacement of the DGPS/INS module are straightforward and do not require special tools.

Control Computer

The table below lists the features tested, the test procedure for conducting the specific test cases, as well as the corresponding acceptance criteria according to the component test plan for the control computer. The test results are listed in the right column, which show that the control computer passed all the acceptance criteria in the table.

Features	Test Procedure	Acceptance Criteria	Test Results
Control computer processor	Power up the control computer, examine the processor status, and execute the 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 the control computer, connect the control computer to a development PC, upload benchmark software and drivers, examine the operating system performance, and test the software development environment including its 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 the control computers to other computers that simulate CAN communication of those components that use CAN interface, and check the 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 the CAN message rate up to 5 times the rate for the normal operation and record the message loss and corruption if they occur.	The CAN interface shall have throughput that meets the specifications defined in the developer's SOW.	Passed. The control computer does not lose any message with a rate up to 200Hz, which is higher than 100hz, the normal rate.
Control computer mechanical design	Subject the computers to moderate vibrations that are severer than those typical to the bus interior in normal operations; test the control computers in the specified temperature range.	The control computer mechanical assembly shall work in the bus/vehicle environment.	Passed.

Features	Test Procedure	Acceptance Criteria	Test Results
Control computer power	Install the control computers into the test bus, connect them to the power from the test bus, and examine the operation of the control computer.	The control computers shall satisfy the power specification for operating in the VAA bus.	Passed.
Control computer environment	After installing the control computers into the test bus and supplying them with power, connect the control computers to the J1939 CAN bus and other components, and examine the correctness of the CAN messages received by and transmitted from the control computers.	The control computer and the associated CAN interface boards shall work in the bus/vehicle environment (electronically, mechanically, and environmentally).	Passed. The control computer correctly receives and transmits CAN messages on all four CAN interfaces simultaneously at the specified rates.
Control computer maintenance	Install and uninstall the control computers, as well as connect them with and disconnect them from other components, and evaluate the 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. The installation and replacement of the control computer are straightforward and does 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 the power fluctuations in the bus 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 table below lists the features tested, the test procedure for conducting the specific test cases, as well as the corresponding acceptance criteria according to the component test plan for the HMI module. The test results are listed in the right column, which show that the HMI module passed all the acceptance criteria in the table.

Features	Test Procedure	Acceptance Criteria	Test Results
HMI module I/O	Turn on and off the switches and examine the HMI digital input readings; output 1 and 0 to each of the digital output and examine the behavior of the 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 the HMI module to moderate oscillations that are more severe than those typical to the bus interior during the bus operations and examine whether the HMI can operate normally under such conditions.	The HMI module mechanical assembly shall work in the bus/vehicle environment and be water resist.	Passed.
HMI module mechanical space	Put the HMI module at several candidate installation locations inside the test bus and check the clearance.	The HMI module assembly shall fit the limited spaces available in the bus.	Passed.
HMI module embedded processor	Operate the embedded processor with the data exchange rate up to 5 times of that in the normal operation and the computation cycle reduced to at least 1/5th of that in the normal operation to evaluate the 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 the HMI module embedded processor to the control computer; and verify the data exchange through the interface.	The embedded processor shall have I/O and data interface capabilities for interfacing with the control computer.	Passed. The two HMI modules communicate with each other and the two control computers through one CAN interface.
HMI module power	Install the HMI module into the test bus, connect them to the power from the test bus, and examine the operation of the 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 the HMI module into the test bus and supplying it with power, connect it to the control computer, and examine the data exchanges and the control of the LED and sound devices.	The embedded processor shall work in the bus/vehicle environment (electronically, mechanically, and environmentally).	Passed. The two HMI modules can communicate with each other and the two control computers through one CAN interface. The two HMI modules control the LED and sound devices as programmed.
HMI module maintenance	Install and uninstall the HMI module, as well as connect it to and disconnect them from the control computers, evaluate the 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.

8.3 Appendix C: Component Integration Test Results

Appendix C presents the results of the integration testing for each of the five major components. The major components that are integrated include the steering actuator, magnetic sensor modules, the DGPS/INS module, HMI modules, and control computers, as well as 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 table below lists the features tested, the test procedure for conducting the specific test cases, as well as the corresponding acceptance criteria according to the component integration test plan for the steering actuator. The test results, listed in the right column, verify that the steering actuator passed all the acceptance criteria in the table.

Features	Test Procedure	Acceptance Criteria	Test Results
Mechanical space	Measure the mechanical space of the steering actuator and compare it with the available space in the bus; after installing the steering actuator into the test bus, examine the 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 the steering wheel and examine the friction and free-play.	The installation of the steering actuator shall not create excessive hard nonlinearities such as friction and free-play.	Passed. The steering wheel turns easily and smoothly. The free-play is about 2-3 degree.

Features	Test Procedure	Acceptance Criteria	Test Results
Steering actuator power	Verify that the steering actuator motor and the embedded processor can operate with the power from the 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 the voltages of the bus battery while the steering actuator is on and off, and verify that the voltages should not change more than one volt.	The power usage of the steering actuator shall not create power surges affecting the existing vehicle electrical systems.	Passed. No observable changes in the voltages of the bus battery.
Steering actuator message content	Store the data communicated to the control computers from the steering actuator, and verify that 1) the data received by the control computers contains the required data contents, 2) the data follows the designed data format, and 3) the values of the data received are consistent with the values sent by the 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. The stored data at the control computers shows that the CAN messages from the actuator are in the designed format and received at the designated frequency.
Control computer message content	Store the data from the control computers to the steering actuator, and verify that the data received by the steering actuator contains the required data contents and format, and the values of the data received are consistent with that sent by the control computers.	The control computer shall provide message ID, mode command, and the corresponding actuator angle and torque commands to the steering actuator.	Passed. The steering actuator indicates that the CAN messages from the control computers were received at the designed frequency and they include all the required content.

Features	Test Procedure	Acceptance Criteria	Test Results
Data communication rate	Store the data communicated between the control computers to the steering actuator on both sides, and verify the 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. Both the control computers and the steering actuator sent and received messages from the other party as designed.
Steering actuator capabilities	Verify that the steering actuator capabilities in sensor range, resolution, accuracy, and torque capacity by following the test procedure described in the component test plan. The procedure is as follows: 1) command the steering actuator motor such that the steering wheel travels its whole range, record the measurements of the angular position sensor, and examine the measurements against the motor specifications, and 2) measure the steering torque applied to the steering column, and examine the measurements against the 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. Both the encoder and the potentiometer measure the full range of the steering wheel travel and maintained the designed resolution. The steering actuator embedded processor provides a torque command to the steering actuator motor, and the maximum torque capacity the rated torque.

Features	Test Procedure	Acceptance Criteria	Test Results
Steering actuator performance	Verify the steering actuator closed-loop servo performance by the following procedure: 1) have the control computers to send various steering angle commands to the steering actuator, 2) read and store the steering angles measured by the steering angle sensors, 3) examine the closed-loop bandwidth, rate and accuracy of response against the 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. The steering actuator achieved better than 1 degree accuracy at steering wheel with a 3-5 Hz bandwidth as specified in the VAA system requirements.

Magnetic Sensor Module

The table below lists the features tested, the test procedure for conducting the specific test cases, as well as the corresponding acceptance criteria according to the component integration test plan for the magnetic sensor module. The test results, listed in the right column, demonstrate that the magnetic sensor module passed all the acceptance criteria in the table.

Features	Test Procedure	Acceptance Criteria	Test Results
Mechanical Space	After installing the magnetic sensor module assembly under the test bus, examine the sensor modules' distance to the side of the bus and their distances to the 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.

Features	Test Procedure	Acceptance Criteria	Test Results
Magnetic field interference	Examine the distance from the magnetic sensor modules to the locations of bus components (such as wheels) that could potentially interfere with the magnetic fields to be measured by the sensor modules. Place a magnet at various locations within the specified range, record the magnetic sensor measurements, measure and record the actual position of the magnet, compare the sensor measurements against the actual positions of the magnet to evaluate the interference from the 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. The mounting locations of the sensor modules were chosen carefully to be away from vehicle components (such as tires) that could impose magnetic interference.
Working environment	Drive the test bus so as to subject the sensor module to moderate oscillations and impacts that are typical during the normal operation of the bus and examine their effects on the magnetic sensor module. Test the sensor module including the connectors and wiring with water for the waterproofness,	The magnetic sensor module assembly shall work in the bus/vehicle environment and any external component shall be water proof.	Passed.

Features	Test Procedure	Acceptance Criteria	Test Results
Magnetic sensor module maintenance	Install and uninstall the magnetic sensor modules, as well as connect them to and disconnect them from the control computers, and evaluate the 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. The install and uninstall of the magnetic sensor module are straightforward and do not require special tools.
Electrical and power supplier	After installing the magnetic sensor modules under the test bus and connecting sensor module embedded processors to the power from the bus, verify the sensor module can operates with the power supply. Drive the bus along a magnetic track, collecting the sensor measurements, and evaluating the sensor measurements to verify the operation of the magnetic sensor module in the bus environment[24].	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.

[24] The robustness as well as the performance of the magnetic sensor modules were continuously evaluated during the component integration testing and the 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 message content	Store the data communicated to the control computers from the magnetic sensor modules, and verify that 1) the data received by the control computers contains the required data contents, 2) the data follows the designed data format, and 3) the values of the data received are consistent with the values sent by the embedded processors of the 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. The stored data at the control computers shows that the CAN messages from the magnetic sensor modules are in the designed format and received at the designated frequency. The CAN messages included all the required content.
Control computer message content	Store the data communicated from the control computers to the magnetic sensor modules, and verify that 1) the data received by the embedded processors of the magnetic sensor modules contains the required data contents, 2) the data follows the designed data format, and 3) the values of the data received are consistent with the values sent by the control computers.	The control computer shall provide the magnetic sensor module with sensor mode command as well as other required operational data.	Passed. The magnetic sensor modules receive the CAN messages from the control computers at the designed frequency and the messages include all the required content.
Data communication rate	Store the data communicated between the control computers to the magnetic sensor modules on both sides, and verify the 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 the control computers and the magnetic sensor modules send and receive messages from the other party as designed.

Features	Test Procedure	Acceptance Criteria	Test Results
Performance evaluation of the magnetic sensor modules	Place a magnet at various locations within the specified range, record the magnetic sensor measurements, measure and record the actual position of the magnet, compare the sensor measurements against the actual positions of the magnet to evaluate the sensor range, resolution, accuracy, as well as the sampling frequency. Select a few fixed locations, place a magnet at the fixed locations several times and record the sensor measurements, compare the sensor measurements corresponding to the same fixed locations to analysis the consistency of the 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. The sensor measurement resolution is 1mm and the consistency of the measurement for any fixed location is also within 5mm. The sensing range for the magnetic sensor module is -105 cm to 105cm with respect to the center of the sensor module.
Magnetic sensor module calibration	Place a magnet at various locations within the specified range, record the magnetic sensor measurements, measure and record the actual position of the magnet, and compare the sensor measurements against the actual positions of the magnet to evaluate the 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. The calibrated sensor module maintained the 5mm accuracy after installation.

Features	Test Procedure	Acceptance Criteria	Test Results
Magnetic sensor module performance	Verify the performance of the magnetic sensor basic signal processing software with the following procedure: 1) drive the test bus through a test track with magnets installed under the pavement, 2) receive and store the lateral deviation from the magnetic sensor modules (the lateral deviation is processed by the embedded processors based on the magnetic field strength measured by the magnetic sensors), 3) examine the smoothness and accuracy of the lateral measurements against the 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 the interference of the shallow and dense re-bars on the track, the lateral position accuracy achieved is about 1~2cm, still within the performance requirements.

One 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 turned out to be the improper termination on the CAN node. Hardware corrections were made to resolve this issue.

DGPS/INS Module

The table below lists the features tested, the test procedure for conducting the specific test cases, as well as the corresponding acceptance criteria according to the component integration test plan for the DGPS/INS module. The test results, listed in the right column, show that the DGPS/INS module passed all the acceptance criteria in the table.

Features	Test Procedure	Acceptance Criteria	Test Results
Mechanical Installation	After the installation, check the location of the GPS antenna as well as the height of any other parts of the DGPS/INS mobile unit that are installed on the 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.

Features	Test Procedure	Acceptance Criteria	Test Results
DGPS/INS module mechanical design	Test the DGPS/INS components that are installed outside of the bus (such as the GPS antenna) with water for waterproofness, Drive the bus so as to subject the module to oscillations and impacts typical during the normal operation of the bus and examine their effects on the module.	The DGPS/INS module mechanical assembly shall work in the bus/vehicle environment and any external component shall be water proof.	Passed.
DGPS/INS module maintenance	Install and uninstall the DGPS/INS mobile unit, as well as connect it to and disconnect it from the control computer, and evaluate the installation/replace procedure.	The enclosure, mounting and connectors of the DGPS/INS mobile unit shall be relatively easy to install and replace	Passed. The installation and replacement of the DGPS/INS mobile unit are straightforward and do not require special tools.
DGPS/INS module power supply	After installing the DGPS/INS mobile unit on the test bus, connect the module to the power from the bus, verify the module can operates with the power supply and are not affected by the 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. The DGPS/INS mobile unit maintains its performance and is not affected by the power fluctuation of the bus.

Features	Test Procedure	Acceptance Criteria	Test Results
DGPS/INS module message content	Store the data communicated to the control computers from the DGPS/INS module, and verify that 1) the data received by the control computers contains the required data contents, 2) the data follows the designed data format, and 3) the values of the data received are consistent with the values sent by the embedded processor of the 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. The stored data at the control computers shows that the messages from the DGPS/INS mobile unit are in the designed format and received at the designated frequency. The messages include all the required content such as time stamp, status, position measurements, confidence, and health signal, etc.
Data communication rate	Store the data communicated from the DGPS/INS mobile unit to the control computers, and verify the 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. The DGPS/INS mobile unit communicates the required data at the required 10 Hz.
DGPS/INS module operational performance	Drive the test bus around a fix course and stop at several fix locations. Evaluate the accuracy and consistency of the 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. The integrated DGPS/INS mobile unit maintained its performance after installation.
DGPS/INS module base station	Drive the test bus around and evaluate the position data collected and stored by the 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.

Features	Test Procedure	Acceptance Criteria	Test Results
DGPS/INS module positioning performance	Verify the performance of the DPGS/INS positioning software with the following procedure: 1) drive the test bus through a test track with magnets installed, 2) read and store the DGPS/INS positions as well as the lateral positions from the magnetic sensor modules, 3) compare the smoothness, consistency, and accuracy of the DGPS/INS positions with those of the lateral positions from the magnetic sensor modules, 4) examine the resultant DPGS/INS positions against the 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. The DGPS/INS mobile unit achieved better than 5cm accuracy under ideal GPS conditions with a clear view of the sky.

HMI Module

For the VAA project, two HMI modules were used for redundancy purpose.

The table below lists the features tested, the test procedure for conducting the specific test cases, as well as the corresponding acceptance criteria according to the component integration test plan for the HMI modules. The test results, listed in the right column, verify that the HMI modules passed all the acceptance criteria in the table.

Features	Test Procedure	Acceptance Criteria	Test Results
HMI module mechanical space	Sit in the driver seat and check the clearance. Drive the bus and check whether the HMI modules would interfere with the 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.

Features	Test Procedure	Acceptance Criteria	Test Results
HMI device accessibility	Sit in the driver seat and check the accessibility of the HMI devices by turning on and off the switches and observing the changes in the LEDs. Drive the bus and check the accessibility of the HMI devices during the 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 the on/off switches and the kill switch are easily reachable by the driver. The location of the LED and sound devices were chosen with inputs from the participating transit agency; the LEDs are easily visible to the drivers and the sound is clear to the drivers.
HMI module mechanical design	Drive the bus to subject the HMI module to oscillations typical to the bus interior during the bus operations and examine whether the HMI modules can operate normally under such conditions.	The HMI module shall work in the bus/vehicle environment.	Passed.
HMI module maintenance	Install and uninstall the HMI modules, as well as connect them to and disconnect them from the control computers, and evaluate the installation/replace procedure.	The enclosure, mounting and connectors of the HMI modules shall be relatively easy to install and replace.	Passed. The installation and replace procedure is straightforward and no special tools are required.
HMI module power	Turn on and off the HMI modules and examine the operation of the HMI modules. Check the power input of the redundant components of the 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. The HMI devices performance is not affected by the power fluctuations of the bus.

Features	Test Procedure	Acceptance Criteria	Test Results
HMI module I/O	Turn on and off the switches and examine the digital input readings of the HMI modules; have the HMI modules output 1 and 0 to each of the digital outputs and examine the behavior of the LEDs and the 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. The HMI modules read the HMI switch inputs as designed, and the LED and sound devices behave correctly according to commands from the HMI module.
HMI module message content	Store the data communicated to the control computers from the HMI module, and verify that 1) the data received by the control computers contains the required data contents, 2) the data follows the designed data format, and 3) the values of the data received are consistent with the values sent by the embedded processors of the 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. The stored data at the control computers shows that the messages from the HMI modules are in the designed format and received at the designated frequency. The messages include all the required content such as module ID, status, fault messages, and health signal, etc.
HMI module feedback to the driver	Program the HMI modules' embedded processors to provide various feedbacks to the driver and evaluate the quality of the 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. The sound device provides a few distinctly different sound patterns for warnings (indicating emergency situations, and system faults) as well as acknowledgement of driver inputs. The LED devices clearly indicate the status of the system.

Features	Test Procedure	Acceptance Criteria	Test Results
Control computer message content	Store the data communicated from the control computers to the HMI modules, and verify that 1) the data received by the embedded processor of the HMI module contains the required data contents, 2) the data follows the designed data format, and 3) the values of the data received are consistent with the values sent by the control computers.	The control computer shall provide ID, system operational status, fault messages, and health signal to the HMI module.	Passed. The data received by the HMI module from the control computer contains all the required information including message ID, system operational status, fault messages, and health signal.
Data communication rate	Store the data communicated between the HMI modules and the control computers on both sides, and verify the 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. The two HMI modules and the control computers communicate with one another at the specified rate without message drop or data error.
HMI module operational performance	Operate the embedded processor with the data exchange rate up to 5 times of that in the normal operation and the computation cycle reduced to at least $1/5^{th}$ of that in the normal operation to evaluate the 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. The integrated HMI modules maintain their performance after they are installed in the test bus.

Vehicle CAN Interface

The table below lists the features tested, the test procedure for conducting the specific test cases, as well as the corresponding acceptance criteria according to the component integration test plan for the vehicle CAN interface. The test results, listed in the right column, verify that the CAN interface passed all the acceptance criteria in the table.

Features	**Test Procedure**	**Acceptance Criteria**	**Test Results**
Mechanical installation	Check the CAN interface controller board installation and wiring. Turn on the control computers and start the engine, check whether the control computer receives the vehicle J1939 CAN messages via the 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. The control computer receives the vehicle J1939 CAN messages via the CAN interface.
Electrical installation	Check the CAN interface controller physical layer isolation and the 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 the bus and drive it around, store the data received from the vehicle J1939 CAN bus while the bus is running; check the stored data to verify 1) the data received contains the required data contents, 2) the rate of the data received looks reasonable and the 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. The vehicle CAN messages provide all the required engine and transmission states, and the vehicle CAN messages are updated and received at 10 Hz, which satisfies the interface requirements.

Features	Test Procedure	Acceptance Criteria	Test Results
Operational performance	Turn on the bus and drive it around with all other CAN communication channels (magnetic sensors, steering actuators and HMIs) on, store the data received from the vehicle J1939 CAN bus while the bus is running; check the stored data to verify 1) the data received contains the required data contents, 2) the values of the data received looks reasonable, and 3) the 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. 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, as well as the other control computer.

The table below lists the features tested, the test procedure for conducting the specific test cases, as well as the corresponding acceptance criteria according to the component integration test plan for the control computers. The test results, listed in the right column, verify that the control computers passed all the acceptance criteria in the table.

Features	Test Procedure	Acceptance Criteria	Test Results
Mechanical space	Examine the clearance around the control computers; drive the test bus around with the control computers turned on; the bus operation shall exhibit the same characteristics as those of when the 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.

Features	Test Procedure	Acceptance Criteria	Test Results
Mechanical design	Drive the test bus to subject the control computers to moderate vibrations typical to the bus interior during normal operations; test the control computers in the specified temperature range.	The control computer assembly shall work in the bus/vehicle environment.	Passed. The control computers perform well in the bus/vehicle environment and they are not affected by the moderate vibrations typical to the bus interior.
Control computer maintenance	Install and uninstall the control computers, as well as connect them to and disconnect them from other components, and evaluate the installation/replace procedure.	The enclosure, mounting and connectors of the control computers shall be relatively easy to install and replace.	Passed. The installation and replacement of the control computers are straightforward and does not require any special tools.
Control computer electrical and power supply	Turn on and off the control computers and examine the operation of the control computers. Check the power supplies to the control computers to make sure they are 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 the data sent and received by both control computers and compare the stored data to verify that 1) the data contains the required data contents, 2) the values of the data received are consistent with the 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 the CAN message from the other control computer at the specified rate and the received CAN message consists of all the required contents.

Features	Test Procedure	Acceptance Criteria	Test Results
Control computer communication rate	Turn on all components (including the control computers, the steering actuator, magnetic sensor modules, the DGPS/INS mobile unit, the HMI modules, and the test bus (to start the J1939 CAN bus)), and examine the rate and correctness (i.e., no missing messages and no errors in the data) of the CAN messages received by and transmitted from the 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. The two control computers send CAN messages to and receive CAN messages from each other at the specified rate of operation.
Control computer operational performance	Turn on all components, and follow the procedure specified in the component testing plan to 1) check the control computer processor performance (throughput, memory, and speed); 2) install and modify software using the software development environment; 3) store data that are received by the CAN messages; and 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 it was installed in the bus.

Integration of Sub-systems

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

The table below lists the features tested, the test procedure for conducting the specific test cases, as well as the corresponding acceptance criteria according to the component integration test plan for combined sub-systems. The test results, listed in the right column, verify that all key sub-systems, as well as their installations to the bus and their appropriate interfaces, satisfied all the acceptance criteria in the table.

Features	**Test Procedure**	**Acceptance Criteria**	**Test Results**
Mechanical installation	Visually examine the installation of any sub-systems to detect any interference between them, check the clearance around each sub-system, drive the bus and check if there is any interference to the normal operations from the installed sub-systems.	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 and off any two to all sub-systems, measure the voltages of the bus battery to examine the effect on the bus electrical systems, and measure the power to each of the sub-systems to detect any 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 was detected.
Electrical installation	Examine the wiring of all sub-systems to verify proper wiring and shielding, measure the terminations, and use a scope to verify that all digital grounds are connected, all power grounds are connected, and the 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.

Features	Test Procedure	Acceptance Criteria	Test Results
Data communication with the steering actuator	With any or all other sub-systems running at the same time, store the data communicated between the control computers and the steering actuator on both sides, and verify that 1) the data received by the control computers from the steering actuator and the data received by the steering actuator from the control computers contains the required data contents, 2) the data follows the designed data format, 3) the values of the data received are consistent with the values sent, and 4) the communication rate is as specified by the 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. The performance of the data communication between the control computers and the steering actuator is not affected by the other VAA components.

Features	Test Procedure	Acceptance Criteria	Test Results
Data communication with the magnetic sensor modules	With any or all other sub-systems running at the same time, store the data communicated between the control computers and the magnetic sensor modules on both sides, and verify that 1) the data received by the control computers from the sensor modules and the data received by the embedded processors of the sensor modules from the control computers contains the required data contents, 2) the data follows the designed data format, 3) the values of the data received are consistent with the values sent, and 4) the communication rate is as specified by the 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. The performance of the data communication between the magnetic sensor modules and the control computers is not affected by other VAA components.

Features	Test Procedure	Acceptance Criteria	Test Results
Data communication with the DGPS/INS module	With any or all other sub-systems running at the same time, store the data communicated from the DGPS/INS mobile unit to the control computers, and verify that 1) the data received by the control computers contains the required data contents, 2) the data follows the designed data format, 3) the values of the data received are consistent with the values sent, and 4) the communication rate is as specified by the 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. The data communication with the DGPS/INS module maintains its performance and is not affected by other VAA components.

Features	Test Procedure	Acceptance Criteria	Test Results
Data communication with the HMI modules	With any or all other sub-systems running at the same time, store the data communicated between the control computers and the HMI modules on both sides, and verify that 1) the data received by the control computers from the HMI modules and the data received by the embedded processors of the HMI modules from the control computers contains the required data contents, 2) the data follows the designed data format, 3) the values of the data received are consistent with the values sent, and 4) the communication rate is as specified by the 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. The Data communication between the control computer and the HMI modules is not affected by other VAA components.
Data communication with the J1939 vehicle CAN bus	With any or all other sub-systems running at the same time, store the data the control computer received from the J1939 vehicle CAN bus, verify that 1) the data received by the control computers contains the required data contents, 2) the values of the data received are reasonable and correct, and 3) the communication rate is as specified by the 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. The communication with the J1939 vehicle CAN bus maintains its performance and is not affected by other VAA components.

Features	Test Procedure	Acceptance Criteria	Test Results
Data communication rate	With all the sub-systems running at the same time, check the communication rate on each of the above channels to verify that the communication rates satisfy the 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 of the data communication can work simultaneously, and each maintains its performance at the specified rate without being affected by other VAA components.
Component operational performance	With all the sub-systems running at the same time, 1) store and verify the data communicated between the control computers, the magnetic sensor modules, the HMIs and the steering actuator are within specifications, and 2) send commands from the control computers to the steering actuator and the HMI modules and verify the 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 the sub-systems running at the same time, each VAA component maintains its own component performance and its communication with other components satisfies the interface requirements.

8.4 Appendix D: University of California VAA Human Factor Study Consent Form

<u>Consent to Participate in the Vehicle Assist and Automation Pilot Program</u>

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, the Director of California PATH, and Wei-Bin Zhang, the Transit Program Leader at California PATH. It is sponsored by Caltrans in partnership with the U.S. Department of Transportation's Federal Transit Authority (FTA) and in partnership with several transit agencies, including your own. The FTA has also independently contracted the University of South Florida's Center for Urban Transit Research to serves as an independent evaluator and reviewer of this research project.

Purpose

The Vehicle Assist and Automation (VAA) project has been proposed to both demonstrate the technical feasibility of transit bus automated lane keeping and automated docking systems and to demonstrate how these systems can improve transit agency operational efficiency, performance and service quality. In this research study, we are outfitting a number of transit busses to have VAA capabilities at specific locations along their routes. When a VAA equipped bus is travelling 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 whether or not the system's usage has an impact on the 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 where an instructor will show you how to use the VAA system, and you 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 the 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, in order 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 6 months or until you are transferred off the VAA equipped routes. Again, 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 travelling 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 only be providing the independent evaluator with de-identified data. 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 takes place during your normal working day, while you are working for your respective 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, you will find 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, you may talk to your supervisor who can relay questions to us, or you may directly contact the project leader, Wei-Bin Zhang, at California PATH, PH: (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, you may contact the office of UC Berkeley's Committee for the Protection of Human Subjects, at (510) 642-7461 or subjects@berkeley.edu.

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

(Signature for participant and observing researcher)