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Fanping Bu, Wei-Bin Zhang, Susan Dickey, Steven E. Shladover, Han-Shue Tan

California PATH Research Report
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This work was performed as part of the California PATH Program of the University of California, in cooperation with the State of California Business, Transportation, and Housing Agency, Department of Transportation, and the United States Department of Transportation, Federal Highway Administration.

The contents of this report reflect the views of the authors who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the State of California. This report does not constitute a standard, specification, or regulation.

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Abstract

Vehicle Assist and Automation (VAA) systems enable lane assist, precision docking and longitudinal control of transit vehicles. They offer the opportunities of providing high quality transit service within reduced lane widths. Transit vehicles in North America are mostly manufactured based on individual transit agencies' customized requirements. The interfaces between VAA components and the mechanical, electrical and electronic systems on the existing transit vehicle, if not defined properly, can be an impediment to large scale deployment of VAA technologies. This report summarizes a research effort in specifying the VAA interface requirements, with a goal to facilitate progress toward the development and deployment of VAA systems on transit vehicles in the U.S., so that transit agencies and their passengers can start to experience the benefits these systems can provide.

Keywords: Vehicle Highway Automation, Lane assist, electronic guidance, Bus Rapid Transit

Executive Summary

The interface requirements defined here are intended to facilitate progress toward the development and deployment of Vehicle Assist and Automation (VAA) systems on transit buses in the U.S., so that transit agencies and their passengers can start to experience the benefits these systems can provide. VAA systems offer the opportunity of providing high quality transit service within reduced lane widths. VAA includes four functions allowing buses to perform precision docking at bus stations, vehicle guidance or automatic steering on the running way between stations, automatic platooning of buses at close separations and fully automated vehicle operations. The precision docking functions facilitate passenger boarding and alighting at stations, while vehicle lateral guidance 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. 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.

The primary technological barrier to VAA deployment is the fact that many of these VAA products are tied to a specific, specialized and costly vehicle and cannot be easily retrofitted onto the existing buses produced by North American bus manufacturers. Whether a U.S.- based or imported VAA system is considered, the prerequisite is that the VAA system must be able to interface with existing bus subsystems.

Transit vehicles in North America are mostly manufactured based on individual transit agencies' customized requirements. 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 large scale deployment of VAA technologies. Therefore, there is a great need to understand how VAA systems, based on any practical technology, can interface with transit vehicles and infrastructure. A standard set of interface requirements will be needed to allow the suppliers to develop VAA technologies with common interfaces and to allow bus manufacturers to retrofit the VAA technologies of transit agencies' choice to different buses without excessive custom design work or modifications to the existing products. These interface requirements are critical to both vehicle manufacturers and suppliers to achieve compatibility, ease of safety verification/certification and to lower cost and reduce deployment time. To address these needs, the U.S. Department of Transportation, through the Federal Transit Administration (FTA) and the ITS Joint Program Office (ITS-JPO) sponsored the project reported herein to study the VAA interface requirements.

In order to clearly define and identify the interfaces between VAA subsystems/elements and bus subsystems/elements, a modular system architecture was established to analyze VAA system functional blocks and information flows. This modular architecture defines the nature of the interface between the VAA system and the bus and bounds the physical interface to a small possible set, therefore is essential for the development of the interface requirements. Based on the modular VAA architecture, interface requirements were developed. The interfaces between

the VAA system and an existing transit bus were classified into three major categories: mechanical, data communication and power supply. Functional units of the VAA system (e.g., lane positioning sensing, vehicle state sensing, steering actuator, brake actuator and propulsion actuator) were analyzed to determine their interface requirements with existing bus subsystems. Special attention was devoted to the data communication, which is the backbone of the proposed VAA system architecture. The interface requirements between buses equipped with VAA systems and infrastructure were also studied in terms of running way width, sensed infrastructure references, boarding platform and vehicle exterior geometry.

Finally, experiments were conducted on an advanced BRT vehicle previously developed by PATH under Caltrans sponsorship, to validate the interface requirements. The experiments were focused on the requirements for data communication, since these cannot be verified by simple inspection of designs or drawings. The SAE J1939 protocol that is popular in the heavy-duty vehicle industry was used for the data communication of the tested system. Aspects of the data communication such as timing and data length were studied.

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List of Abbreviations

ABS: antilock braking system
ADA: Americans with Disabilities Act
AVCSS: Advanced vehicle control and safety systems
BRT: Bus Rapid Transit
CAN: Controller Area Network
CNG: compressed natural gas
CSMA/AMP: Carrier Sense Multiple Access / Arbitration by Message Priority
DOP: dilution of precision
EBS: electronic braking system
ECM: electronics control module
ECU: Electronic Controller Unit
FHWA: Federal Highway Administration
FTA: Federal Transit Administration
GCM: governor control module
GPS: Global Positioning System
HMI: Human Machine Interface
INS: Inertial navigation system
JPO: Joint Program Office
OSI: Open System Interconnection
PATH: Partners for Advanced Transit and Highways
PLC: programmable logic controller
ROW: Right of way
SAE: Society of Automotive Engineers
SBAS: Satellite Based Augmentation System
TTCAN: Time-Triggered CAN
TTP: Time-Triggered Protocol
UPS: Uninterrupted power supply
UTC: Coordinated Universal Time
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
VDC: volts of direct current
VRS: Virtual Reference Station (for differential GPS)

1.0 Introduction

Transit agencies throughout the United States (U.S.) 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, Bus Rapid Transit (BRT) is seen as a cost-effective alternative to more conventional fixed guideway systems that are becoming increasingly expensive to construct and operate. As current funding (both federal, state and local) for conventional fixed guideway transit is becoming more limited, transit agencies have to come up with more cost effective alternate modes. In the recent development of BRT systems, where new construction does not take place, new BRT lanes are being carved out within existing 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.

Lane Assist or Vehicle Assist and Automation (VAA) systems offer the opportunity of providing high quality transit service within reduced lane widths. VAA includes four functions that can transfer portions of the bus driving responsibility from the driver to the VAA system: VAA-PD provides for precision docking at bus stations, VAA-VG provides for vehicle guidance or automatic steering on the running way between stations, 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 initial and 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 rail cost. BRT buses equipped with VAA technologies could provide a similar level of service as conventional fixed guideway systems with the same, if not more, benefits. From the driver's perspective, the VAA system can be a means to decrease workload and stress while at the same time allowing him/her to operate in more challenging environments (e.g., narrower lanes). For passengers, the implementation of an electronic guidance system will mean smoother operation, faster and safer boarding and alighting, better schedule reliability, and increased mobility for ADA riders.

To address the needs of the transit industry, the U.S. Department of Transportation, through the Federal Transit Administration (FTA) and the ITS Joint Program Office (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 six out of nine typical transit operating scenarios would benefit from VAA technologies and there is a defined market for VAA technologies. 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. VAA is now being considered as a larger scale demonstration program. Currently, VAA systems are being marketed towards Bus Rapid Transit (BRT) systems that are beginning to operate in the U.S.

One concern that was raised as part of the VAA Tier II Exploratory project was how VAA technologies could be made commercially available in the United States; current commercially available VAA technologies are only offered by overseas vendors. Although U.S. research institutions have developed various VAA technologies and in some cases pioneered the technology development (e.g., magnetic guidance and vehicle platooning), none of these technologies are commercialized yet. There is indeed an urgent need for U.S.-based commercial VAA systems. Some transit agencies have been looking for foreign VAA products to meet their immediate needs. However, there are a number of institutional and technological hurdles that U.S. transit agencies must face in order to deploy imported VAA technologies. The primary institutional barrier is the Buy America regulations that limit the ability of U.S. transit agencies using federal funds to acquire VAA technologies sold by non-U.S. companies. The primary technological barrier is the fact that many of these VAA products are tied to a specific, specialized and costly vehicle and are difficult to retrofit onto the existing buses produced by North American bus manufacturers. Whether a U.S.-based or imported VAA system is considered, the prerequisite is that the VAA system must be able to interface with existing bus subsystems.

The overall goal of this study is to develop interface requirements allowing VAA systems to be able to interface with commercially available buses in North America. The project objectives are:

- Understand the needs, technical issues and challenges for VAA technologies to interface with vehicles;
- Develop interface requirements for both the VAA systems and the vehicles, allowing maximum compatibility, as well as requirements for the vehicle to roadway infrastructure interfaces;

- Conduct case studies of the BRT applications for two partner agencies; and
- Test selected interface requirements using PATH's test vehicle.

1.1 Needs for VAA Interface Requirements

Transit vehicles in North America are mostly manufactured based on individual transit agencies' customized requirements. As an industry common practice in the United States, the bus components such as engine, power steering system and pneumatic brake system are developed by a variety of suppliers (e.g. Cummins and Detroit Diesel for engines, Allison for transmissions, TRW and R. H. Sheppard for power steering system, WABCO and TRW for pneumatic brake system). The existing bus manufacturing practice is such that different bus manufacturers have the liberty of using different components provided by different suppliers. Although certain requirements are established industry-wide, most of the system requirements are driven by individual designs and component suppliers. On the other hand, several VAA technologies have been developed by different suppliers (e.g., guidance systems based on magnetic sensing, differential global positioning system integrated with inertial navigation systems and video image processing). Different transit agencies may want to implement one specific VAA technology or even combine multiple VAA technologies on their selected buses according to their specific operating conditions and scenarios. 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 large scale deployment of VAA technologies. Therefore, there is a great need to understand how VAA systems, based on any practical technology, will interface with transit vehicles and infrastructure.

In order to facilitate VAA deployment, a standard set of interface requirements will be needed to allow the suppliers to develop VAA technologies with common interfaces and to allow bus manufacturers to retrofit the VAA technologies of transit agencies' choice to different buses without excessive custom design work or modifications to the existing products. These interface requirements are very critical to both vehicle manufacturers and suppliers to achieve compatibility, ease of safety verification/certification and to lower cost and reduce deployment time. The standard interfaces are also crucial to the transit operators for maintenance. Specifically, interface requirements are needed in the following areas:

1.1.1 Electronic Guidance

A VAA-VG or VAA-PD system contains three major components: a set of sensors, actuators and a processor. Among these components, the steering actuator has the closest interaction with existing vehicle components.

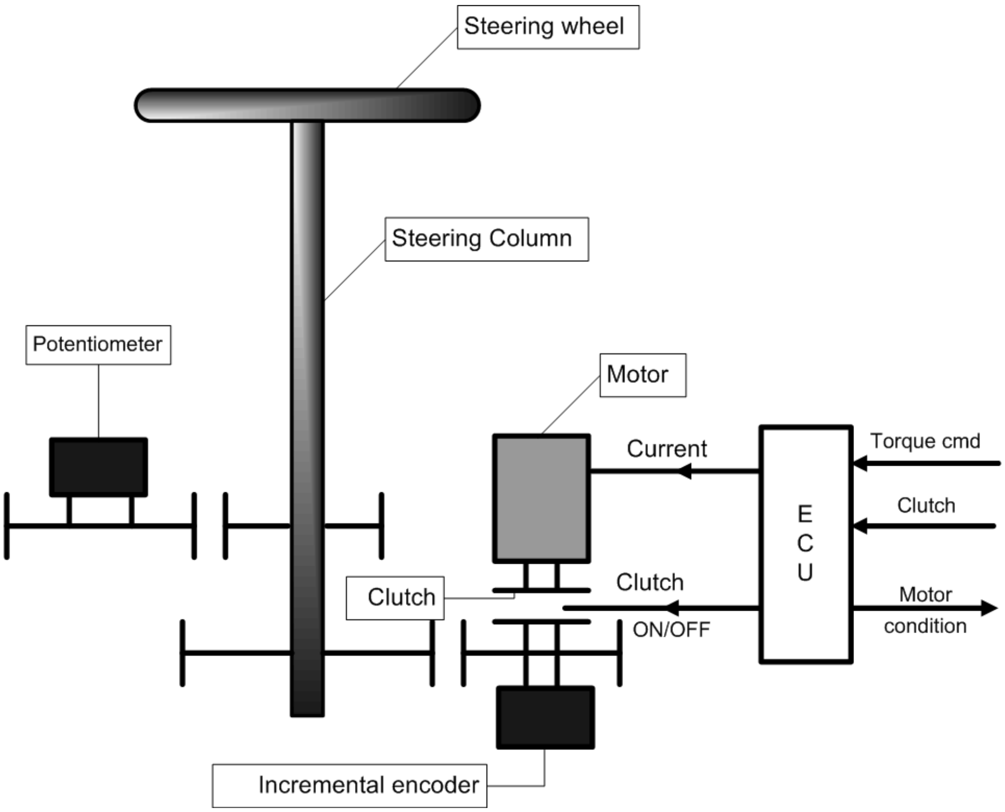


Figure 1.1 Schematic of electric steering actuator hardware

An electric steering actuator design, as shown in Figure 1.1, consists of a steering column, a DC motor actuating the steering column, an electromagnetic clutch and angle sensors measuring steering wheel position. Various interfaces exist between the add-on components and the bus steering column. The DC motor connects to the steering column through a clutch and reduction gear. An incremental encoder is mounted on the motor shaft to measure the relative position of the steering wheel. A multi-turn potentiometer is connected with the steering column shaft via pulley gear and belt to measure the absolute position of the steering wheel. Motor current and clutch ON/OFF are controlled by an Electronic Controller Unit (ECU), which receives a torque command from an upper level computer and issues corresponding current commands so that the DC motor will generate the required torque. The clutch can also be controlled by the upper level computer by issuing a clutch command to the ECU. The ECU has built-in self-diagnostic features. The health condition of the motor is fed back to the upper level computer through the motor condition signal. Because these additions can be standardized, interface requirements are needed to specify the interface between the necessary add-on components and the current steering mechanism. Additionally, the performance of some of the interface components may also need to be addressed. For example, some of the existing power assist systems are designed with excess freeplay, which makes it very difficult to develop a guidance system that will provide good tracking accuracy. Corresponding to the performance requirements for the guidance system, there is also a need to define performance requirements to enable the bus steering mechanism to support the performance requirements of the complete electronic guidance system.

1.1.2 Longitudinal control

Automated longitudinal control, in conjunction with electronic guidance, enables smooth operation within the BRT lane and high precision stopping at the bus station.

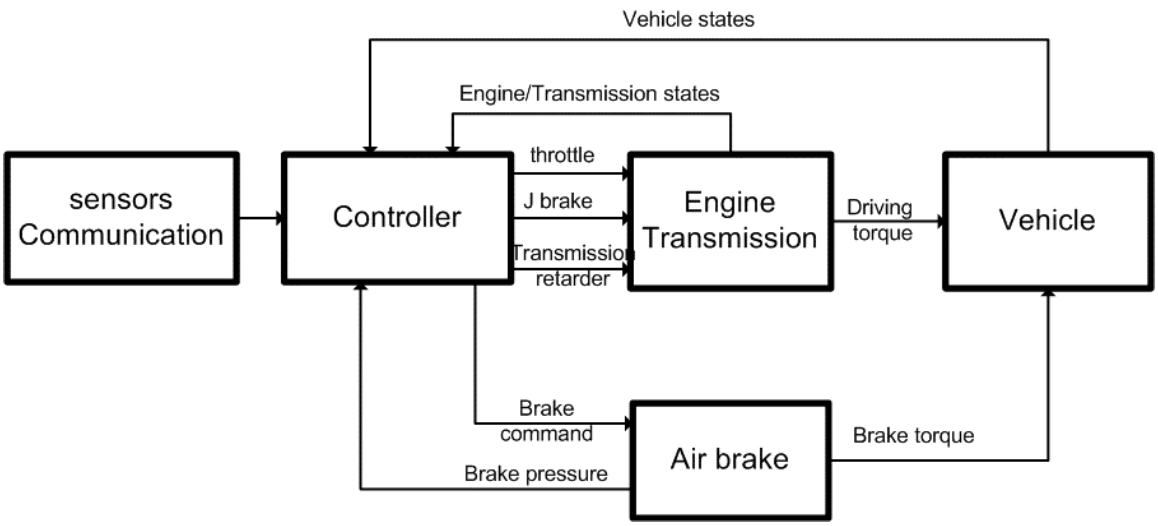


Figure 1.2 Longitudinal control diagram

Figure 1.2 shows a schematic of the longitudinal control data flow. The longitudinal controller sends a throttle command to the engine and transmission through either the J1939 data bus or added electronics. Depending on the transmission model, a transmission retarder may or may not be available for control purposes. Most engine and transmission state information (e.g. engine speed, engine torque, torque converter lockup, current gear etc) can be accessed via the J-Bus. By retrofitting changes to the existing air brake system, the longitudinal controller can send brake commands to control the air pressure inside the brake chamber. Vehicle states such as wheel speed and longitudinal acceleration can be available on the J-Bus or from added sensors (accelerometer).

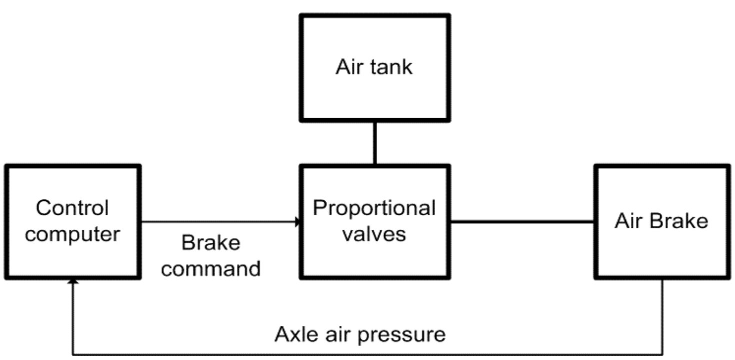


Figure 1.3 An example of a bus brake actuator

The brake actuation may need to be retrofitted on the existing air brake system. As shown in Figure 1.3, the control computer sends out brake commands and the proportional valves regulate the air pressure inside the air brake system according to the received brake command. The most important interface requirements for the brake actuator are how quickly and how accurately the brake actuator can build up or release the air pressure required by the brake command.

1.1.3 Functions of In-Vehicle Networks

All modern buses use an in-vehicle data network. In buses powered by both Cummins engines and Detroit Diesel engines, the engine, transmission, and braking systems are all controlled by a separate Electronic Control Module (ECM). These ECMs communicate via in-vehicle serial networks to receive sensing and diagnostic reports and to issue control commands. Most transit buses use one of three types of in-vehicle networks, namely: SAE J1587, SAE J1922, and SAE J1939, among which the SAE J1939 network alone can provide the desired data communication for vehicle control applications. Figure 1.4 shows an example of control functions implemented using J1939 on New Flyer buses. In order for a VAA system to accomplish assist or automatic control functions using the existing on-vehicle sensing and actuation functions, communication through an existing in-vehicle network is essential. However, existing in-vehicle networks cannot accommodate all VAA communication needs. There is a critical need to develop a dedicated safety critical in-vehicle network to handle VAA-specific communication needs. This dedicated VAA in-vehicle network, whether it is implemented using J1939 or other technologies, must be able to work with the existing in-vehicle network and the VAA subsystems discussed in this report. Therefore, interface requirements including communication protocols must be defined.

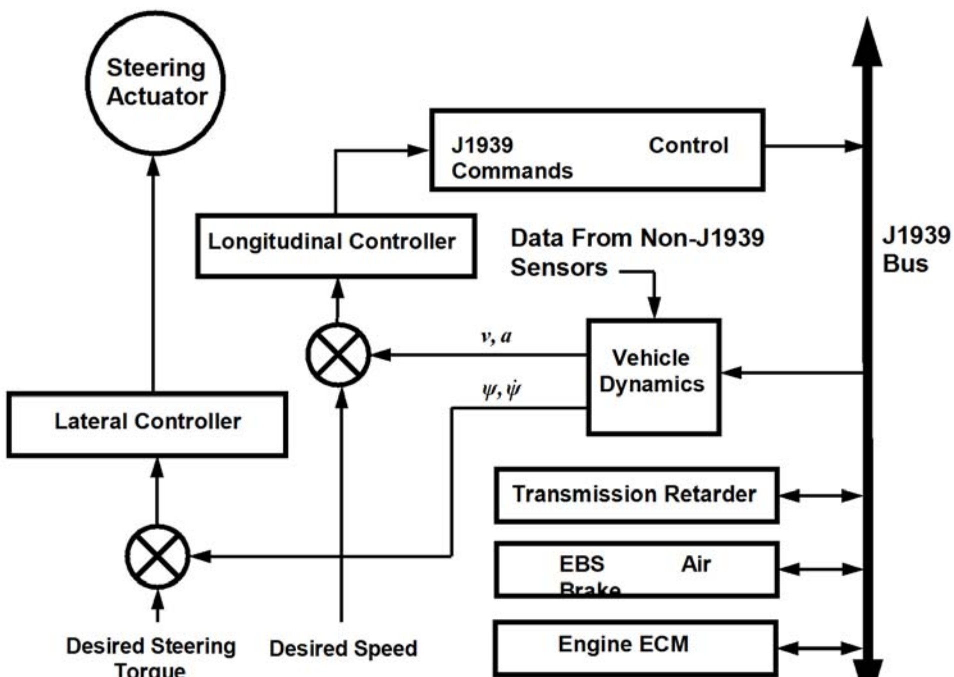


Figure 1.4 Sensing and Actuation for Lateral and Longitudinal Control using J1939 Serial Network

1.1.4 Vehicle - Infrastructure Interface

Certain station/stop maneuvers, particularly the S-curve docking operation, may not bring the bus to a stop parallel to the platform. 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. Only when the design of the vehicle and the configuration of the platform are in harmony, can the buses be precisely docked at the bus stop. Since station designs will need to be very site specific, a set of design recommendations are needed.

1.2 Interface Requirements vs. System Requirements and Designs

While the purpose of VAA interface requirements is to define a common set of interfaces between VAA technologies and the existing and future buses and components, they are not intended to directly address the system level requirements. However, the VAA interface requirements need to be consistent and compatible with the potential VAA system designs and to support VAA system requirements that specify performance, reliability, safety and maintainability of the system.

Interfaces are closely tied with VAA system designs. There can be various design philosophies for implementing a VAA system, ranging from a 'fully integrated approach' that requires bus and VAA components to be designed interactively to achieve maximum integration to the 'add-on approach' that would design VAA components to fit onto buses from different vendors with minimum modification of existing bus components. The Phileas bus developed by APTS in the Netherlands is an example of a fully integrated approach, which involved an integrated design from the ground up. The automated functions of Phileas were designed in conjunction with the bus basic driving functions, thereby achieving maximum integration. 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. Add-on designs, though less integrated than the 'integrated approach', support stand alone components to fit onto existing buses and therefore could likely have wider applications. From the interface perspective, an integrated VAA system will unlikely require standard interfaces for VAA components and newly designed buses, whereas it is very important to have standard interfaces when VAA components and systems are 'add-ons' to existing buses. Therefore, the interface requirements being studied under this project are specifically for 'add-on' VAA components and systems. 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 VAA system requirements may include system performance specifications and technical specifications. Collectively, these specifications will define the operation conditions and environments and will specify the performance, reliability, safety, and maintainability of the system.

The VAA system requirements can impact or be impacted by the VAA interface requirements, either directly or through system designs. Under the FTA sponsored project ‘Development of Needs and Requirements for Transit Lane Assist Systems’, draft performance requirements were developed. Based on these requirements and prior extensive knowledge of VAA technologies, this project team established the following considerations for the VAA interface requirements.

1.2.1.1 Interface Requirements vs. Performance Requirements

There are a number of ways that the interface requirements can impact or be impacted by the overall system performance. 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. The vehicle-infrastructure interface could also affect how a VAA system performs within the BRT running way and at bus stations. There is therefore a need to address the interaction between the interface requirements and performance requirements through analysis or verification tests to validate the impacts of the performance requirements to ensure that the interface requirements can adequate support a high performance VAA system.

1.2.1.2 Safety Design Considerations

There is no doubt that all VAA functions are safety-critical. VAA systems may include both fully automated as well as driver assist functions. In a driver assist system, a driver can become a portion of the system and could take over the control and be responsible for ultimate safety, while the fully automated VAA system must be designed to deal with system faults and to prevent hazardous conditions from occurring. No matter whether VAA involves driver assist or fully automated operation, it is imperative that the overall system remains fail-safe (capable of compensating automatically and safely for a failure) or fail-soft (capable of operating at a reduced level of performance and efficiency after the failure of a component or power source) in the event that a hazardous failure occurs. However, in designing a safety critical system, it is a common practice that the smallest possible set of safety critical functions are isolated within a portion of the system in order to reduce the complexity of the overall system design. For a VAA system, it is imperative that this design philosophy be followed and the safety critical functions be designed within the VAA components or system, but no fail-safe requirements be imposed on existing bus components.

Safety requirements are often implemented through redundancy or fail-safe designs. Safety designs typically involve hardware redundancy and software redundancy. Hardware redundancy can affect the interface the most if the safety design is propagated to vehicle components. 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 vehicle components. On the other hand, the interface requirements need to support fault diagnosis and software redundancy.

Note that safety design of the VAA requires systematic analyses, which typically would involve defining the system safety levels, hazard analysis, failure mode effects and criticality analysis, functional decomposition and identification of safety critical functions. The project team has conducted significant safety analysis of various VAA functions. However, this analysis is not at the scale that would result in a comprehensive definition of system safety. The project team recommends a systematic analysis be planned within the upcoming VAA program in order to address the safety requirements and design issues.

1.2.1.3 Reliability Considerations

Reliability is customarily measured in terms of the mean time between failures (MTBF) of infrastructure and onboard systems, subsystems, and components. 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. The reliability of the interface requirements therefore should be at the same level as the system reliability requirements.

1.2.1.4 Other Design Considerations

VAA systems should be at least as durable as other onboard systems so that the current service cycle can be maintained (every 12,000 miles in the case of Lane Transit District, Eugene, OR). 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 modules and replacing them by the maintenance staff will be easier, and spare modules will be more like commodity items than specialty items. Interface requirements should support the modular designs.

At the present time the service life of a bus is approximately 20 years. Given the current pace of changing technology, the interface requirements may also need to support future upgrades to be backwards compatible so that the entire system will not have to be replaced.

The requirements and design aspects have been considered in the process of development of the VAA interface requirements summarized in the final report.

1.2.2 Development of Interface Requirements – Project Overview

In order to begin to address these technological barriers and to facilitate the development and commercialization of VAA technologies for existing transit vehicles, the FTA and ITS-JPO funded the research effort to develop interface requirements. A team consisting of Lane Transit District, AC Transit, California Department of Transportation, and the University of California PATH Program was selected to develop the interface requirements. Lane Transit District and AC Transit are members of the BRT Consortium. These agencies have planned dedicated BRT routes and are convinced that VAA technologies can offer benefits in enhancing the efficiency, safety and quality of BRT service. Caltrans has been a leading agency supporting development of advanced technologies for transportation industries, and has devoted significant funding to sponsor research and development of advanced vehicle control and safety system (AVCSS) technologies. Caltrans is interested in supporting the implementation of AVCSS technologies on transit and other vehicles in order to improve traffic operations and decrease congestion.

California PATH, a world-wide leader in the development of advanced vehicle sensing and control systems, has developed several guidance technologies that have demonstrated superior performance and practicality for real world deployment. The Gillig, New Flyer and VanHool bus manufacturers have provided support and information on their bus products. The objectives were implemented in the project milestones described below.

1.2.3 Assessment of Existing Buses and Supporting Infrastructure Relevant to VAA

As the first step toward the interface requirement definition, a representative selection of existing transit buses was investigated. Based on extensive knowledge of both VAA systems and the bus subsystems, the team took a systems approach to investigate bus designs from Gillig, New Flyer, NABI and VanHool. This investigation focused on the relevant bus subsystems such as steering, engine/transmission, brake, in-vehicle network, electrical and exterior geometry, all of which are directly related to the implementation of a VAA system.

1.2.4 Develop Interface Requirements

In order to clearly identify the system interfaces between VAA subsystems/elements and bus subsystems/elements, a modular system architecture was established. This modular architecture defines the nature of the interfaces between the VAA system and the bus and bounds the physical interfaces to a small possible set, therefore is essential for the development of the interface requirements. Based on the modular VAA architecture, interface requirements were developed. The interfaces between the VAA system and the transit bus were classified into three major categories: mechanical, data communication and power supply. Functional units of the VAA system (e.g. lane positioning sensing, vehicle state sensing, steering actuator, brake actuator and propulsion actuator) were analyzed to determine their interface requirements with existing bus subsystems. Special attention was placed on the data communication, which is the backbone of the proposed VAA system architecture. The interface requirements between buses equipped with VAA systems and infrastructure were also studied in terms of running way width, sensed infrastructure references, boarding platform and vehicle exterior geometry.

1.2.5 Testing of the Requirements

After the interface requirements were developed, a New Flyer bus that was previously instrumented by PATH with VAA capabilities was modified to emulate the electronic interfaces between VAA and existing bus controls. The emulated interface was tested on the test track in order to validate that the proposed interface requirements are technically feasible. A sequence of verification tests was conducted to quantitatively validate the feasibility of the proposed requirements.

1.3 Report Organization

This report summarizes the findings on the needs for and the feasibility of interface requirements based on a thorough study of several transit buses and various VAA technologies. It also defines the interface requirements for VAA. These requirements are intended as recommendations to FTA and the transit standard organizations for the development of VAA related interface standards. They can also be used by transit agencies that are considering early deployment of VAA systems as a basis for developing requirement specifications for the selected VAA systems and by VAA system suppliers and bus manufacturers as a reference for interface designs in the absence of official VAA standards. The remaining report is organized as follows:

Section 2.0 reports the results of detailed investigations of buses and component technologies from several major bus manufacturers and suppliers. Special attention was placed on the assessment of the suitability of the existing buses as platforms for implementing VAA systems.

Section 3.0 reports the results from an evaluation of bus station configurations, focusing on designs provided by LTD and AC Transit, and recommended a set of requirements imposed on the infrastructure for interfaces to a bus equipped with VAA systems.

Section 4.0 reports steps that took place to develop interface requirements for vehicle-borne system functions. It discusses functional blocks and modular VAA architecture and recommended VAA interface requirements for in-vehicle VAA systems, including the data communications between subsystems.

Section 5.0 reports the tests carried out to validate the utility of the interface requirements.

Section 6.0 Conclusions regarding the VAA interface requirements and issues are presented.

2.0 Investigation of Existing Transit Bus Sub-Systems

Developing vehicle assist system interface requirements requires extensive knowledge of the existing transit bus sub-systems that will be interfaced with the new vehicle assist components. As the first step toward developing the interface requirements, several existing transit buses were investigated including a New Flyer 40' CNG, a New Flyer 60' Diesel, a Gillig 40' low floor, a VanHool 40' and a VanHool 60'. These buses were chosen for two primary reasons. First, they were readily available to the researchers for detailed study; and second, they have significantly different characteristics, which together represent a broad range of transit buses (i.e. single unit vs. articulated, CNG vs. diesel and domestic manufacturer vs. foreign manufacturer). This chapter summarizes the current configurations of these buses, focusing on the bus subsystems that are important for vehicle assist, and describe the tests that were performed on these buses and the results obtained from those tests. The summary covers the steering system, engine/transmission, brake system, in-vehicle network, electrical system and exterior geometry, all of which are directly related to the implementation of a vehicle assist system. The information collected here provides an important set of background knowledge, on which the subsequent requirements definition work can be built.

2.1 Objectives and Procedure

VAA systems are most likely to be designed as add-on or retrofit systems, to be connected to existing vehicle subsystems. The add-on system design introduces multiple interactions with existing vehicle subsystems. In order to perform VAA functions such as lane guidance, precision docking and longitudinal speed control, the VAA system has to access the existing bus's subsystems (e.g. power steering, engine/transmission and pneumatic brake) to obtain the desired steering angle, driving force and braking force. The operation of 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 for ABS). 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 (electrical, hydraulic or pneumatic) 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 in current use. The sub-systems and components that affect vehicle assist functionality include the physical shape and dimensions of the bus exterior and interior, steering mechanism, engine/transmission, brake system, data network and power systems. Field trips were made to a transit agency, a bus manufacturer and the APTA Expo 2005 to gather information about existing bus subsystems. The effects of the existing vehicle subsystem designs on the future integration of VAA systems into buses were assessed based on the information collected from these field trips, the experience with VAA technology implementation in prior PATH experimental projects, and inputs from transit agencies and bus manufacturers. This information can support the definition of guidelines for transit agencies and bus manufacturers regarding the design of buses suitable for VAA retrofitting. At the same time, this information is useful in helping the VAA technology developers to adapt their technologies to work on the widest possible range of buses.

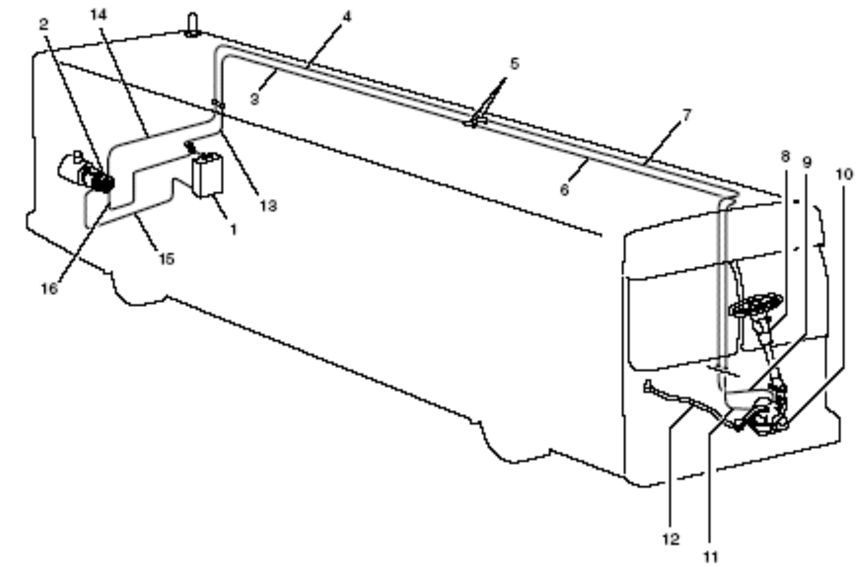
2.2 Power Steering System

Power steering is a system for reducing the steering effort required of drivers by using an external power source to assist in turning the wheels. Hydraulic power steering (HPS) uses hydraulic pressure supplied by an engine-driven pump, and is popular among heavy duty vehicles.

The primary focus of the current work is on the vehicle assist functions associated directly with steering of the bus (precision docking and vehicle lateral guidance). 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 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.

2.2.1 New Flyer 40' CNG and New Flyer 60' Diesel

Figure 2.1 shows the power steering system manufactured by R. H. Sheppard for the New Flyer 40' CNG bus and New Flyer 60' Diesel articulated bus. It consists of a hydraulic pump, a reservoir and a power steering gear box. The hydraulic pump supplies pressurized hydraulic fluid to the hydraulic circuits. When the driver turns the steering wheel, the power steering gear box will provide enough power assist according to the torque sensed by the torsion bar. Figure 2.2 shows how the steering column assembly is connected to the power steering gear box.



1. Reservoir Assembly, Power Steering/Hyd. Fan
2. Pump Assembly, Power Steering
3. Tube Assembly, Power Steering Rear Return
4. Tube Assembly, Power Steering Rear Supply
5. Union, 3/4" O.D. x 3/4" PT.
6. Tube Assembly, Power Steering Front Return
7. Tube Assembly, Power Steering Front Supply
8. Steering Column Assembly
9. Hose Assembly, FC300-10
10. Gear Box Assembly, Power Steering
11. Hose Assembly FC300-10
12. Drag Link Assembly
13. Hose Assembly, FC300-12
14. Hose Assembly, FC300-8
15. Hose Assembly, FC350-16
16. Hose Assembly, FC300-10

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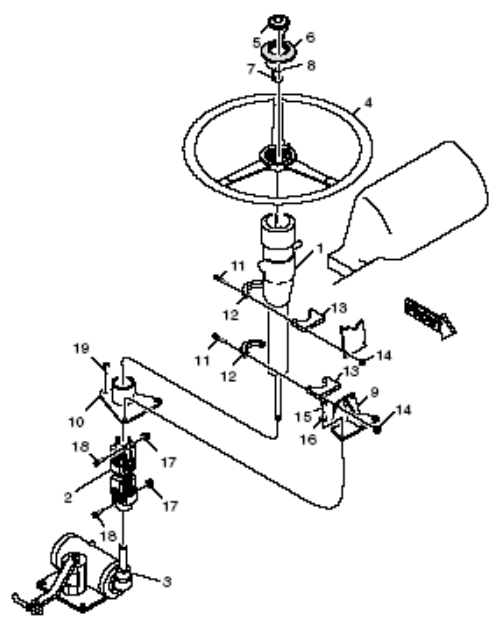
Figure 2.1 New Flyer Power Steering Systems



1. Steering Column Assembly
2. Steering Joint Assembly
3. Gear Box Assembly, Power Steering
4. Steering Wheel
5. Button, Horn
6. Cap, Steering Wheel
7. Ground Wire Assembly
8. Nut, 7/8" - 20
9. Support Assembly, Steering Column
10. Support, Lower Column
11. Screw, Socket Cap 5/16" x 3 1/4" Lg.
12. Clamp, Aft
13. Clamp, Fore
14. Nut, Lock Nylon 5/16" - 18 UNC
15. Screw, PH Cross Recess Tpg. Type F 1/4" - 20 UNC x 2" Lg.
16. Washer, Lock Spring Type SS 1/4"
17. Nut, Lock Nylon 3/8" - 24 UNC
18. Bolt, Hex 3/8" - 24 UNF
19. Screw, PH Cross Recess Tpg. Type AB 1/4" x 1" Lg.

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Figure 2.2 New Flyer Steering Column Installation

Figure 2.3 shows the actual steering wheel and steering column assembly on the two New Flyer buses. There is very limited space available for the addition of the steering actuator on the steering column, as shown in the photos.

Figure 2.3 New Flyer steering wheel and column (left 40' CNG; right 60' Diesel)

2.2.2 Gillig 40' Low Floor

The steering system of the Gillig 40' Low Floor bus is manufactured by TRW. Figure 2.4 shows the hydraulic loop. The steering system consists of the steering wheel, steering column and shaft assembly, and power steering gear box. The steering column extends through the floor and, using a universal joint, attaches directly to the input shaft of the power steering box. The power steering box provides hydraulic power assist when the driver turns the steering wheel. Figure 2.5 shows the actual steering wheel and steering column assembly. There is very limited space for the addition of the steering actuator as shown in the photos.

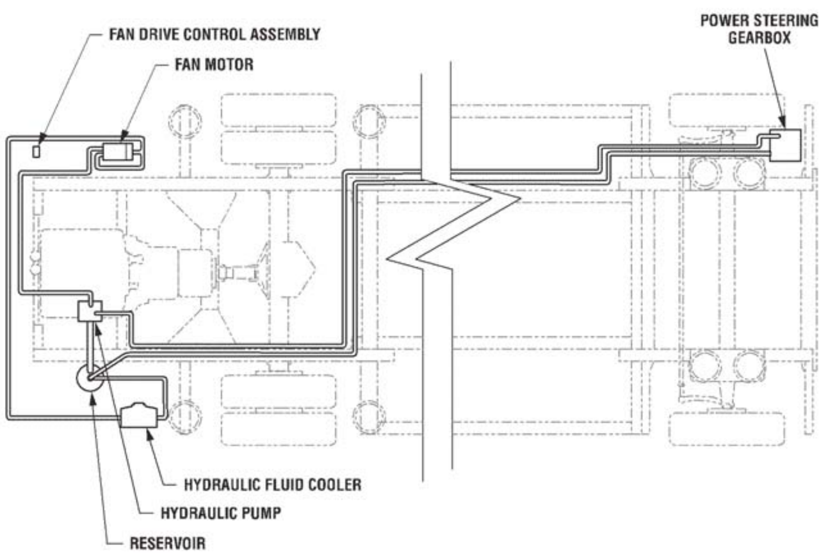


Figure 2.4 Gillig Hydraulic Power Steering System

Figure 2.5 Gillig Steering Wheel and Column

2.2.3 VanHool 40' and 60'

Figure 2.6 shows the steering wheel and column installation for both VanHool 40' and 60' buses. There is very limited space for the addition of a steering actuator as shown in the photos. One particular problem associated with the VanHool 60' bus is that the trailer wheel will steer with the front steering wheel when the trailer angle is larger than a certain threshold. This may become a design constraint for the departure trajectory design of the precision docking maneuver.

Figure 2.6 VanHool Steering Wheel and Column (left 40', right 60')

2.2.4 Field Testing of Power Steering System

Since the steering actuator is the most important actuator for the lateral control of VAA functions, tests were performed to study the static characteristics of the available bus power steering systems that are relevant to steering actuator design. These systems include a New Flyer 40' CNG and a New Flyer 60' diesel bus. Visits took place at the SAMTRANS (San Mateo County Transit District) and AC Transit maintenance yards for testing of the Gillig 40' low floor bus and VanHool 40' and 60' buses.

Tests were performed while the buses are stopped on a paved road with the engine running. A constant torque M was applied at the steering wheel to move the bus front wheels at a constant rotation speed. Tests were also performed to determine the amplitude of the steering mechanism freeplay. The test results are summarized in Table 2.1.

Table 2.1 Power Steering System Testing Results

	New Flyer 40' CNG Bus	New Flyer 60' Diesel Bus	VanHool 40' Bus	VanHool 60' Bus	Gillig 40' low floor Bus
Steering torque (Nm)	7.9	10.6	4.4	5.2	2.0
Freeplay (degrees at steering wheel)	≥ 25	≥ 25	≤ 5	≤ 5	≤ 5

Both New Flyer buses are equipped with the same power steering system, manufactured by R. H. Sheppard, but the New Flyer 60' Diesel has heavier steering due to its body weight. The existing power steering gear box has some nonlinear characteristics, which increase the difficulty of control design for electronic guidance purposes.

- The power steering gear box has large free play (about 25 degree steering wheel angle).
- The power steering gear box cannot provide enough power assist, especially when the bus speed is low.
- The power assist curve is generally not symmetric for opposite turning directions (e.g. left turn or right turn).

The Gillig 40' low floor bus's TRW power steering system is more powerful. It has a smaller steering wheel (0.5 m in diameter compared with 0.56 m for New Flyer buses) and smaller freeplay in the steering mechanism. The steering torques in Table 2.1 could provide useful guidance when selecting the components for an add-on steering actuator design (e.g. the torque capabilities of the DC motor for the add-on steering actuator design).

The power steering systems on the VanHool 40' and 60' buses show similar characteristics to the Gillig 40' low floor bus's TRW power steering system, but with slightly higher steering torque required.

2.2.5 Summary

The design of power steering systems is quite mature, and all the power steering systems investigated showed similar designs. However, the characteristics of the power steering systems, especially those related to VAA system functionality differ considerably from system to system. For example, the power steering systems of both New Flyer buses have significant freeplay, which makes steering actuator design for a VAA system very difficult. On the contrary, the power steering systems of both VanHool buses and the Gillig bus have very small freeplay (less than 5 degree in steering wheel angle). Secondly, the space available for the installation of a steering actuator is very limited around the steering columns of all the buses, so a compact steering actuator design will be necessary.

2.3 Pneumatic Brake System

The pneumatic brake system uses compressed air to deliver the desired braking force at each wheel's brakes, and is widely used in heavy duty vehicles. When the driver presses the brake pedal, the treadle valve is opened and compressed air flows from the air tank to the brake chambers. The brake chamber is a diaphragm actuator which converts the energy of air pressure to mechanical force, which is transmitted to the brake pad through the push rod and brake cam. Brake force is generated by the friction between the brake pad and brake drum. Air is released to the atmosphere when the driver depresses the brake pedal. The compressor is turned on to recharge the air tank when the air tank pressure drops below a minimum threshold level.

If longitudinal speed control or longitudinal precision stopping is required for the VAA system, the brake actuator system has to actuate the bus's existing pneumatic brake system to deliver the desired brake force. The addition of a brake actuator to a bus involves a variety of design and interface considerations that need to be done carefully because any failure in the braking function would have obviously adverse safety consequences. The brake actuator needs to be able to engage sufficient braking force to stop the vehicle under the anticipated operating conditions, while controlling the braking force accurately enough to ensure that the braking action is smooth enough to promote passenger comfort. This requires thorough knowledge and understanding of the existing braking systems on the buses that may be equipped for VAA.

2.3.1 New Flyer 40' CNG

The New Flyer 40' CNG bus is equipped with an S-cam pneumatic brake system. The on-board air supply is from an engine-driven air compressor running at engine speed (Figure 8.8 in Appendix B). The air system is controlled by a governor. When air pressure in the wet tank is below 105 psi, a signal is sent to the governor to close the valve in the dryer and start compressing air into the system. The brakes are applied by depressing the brake foot treadle to activate the brake foot valve. This causes air to flow from the supply side of the valve to the delivery side. Once compressed air enters the brake chamber, it drives the S-cam and applies brake force on the brake drum. Depressing the brake treadle applies a modulated control signal to the front quick release valve supply port. The quick release valve supplies air through the ABS modulator (

Figure 8.9 in Appendix B) valves which control the supply to the left and right brake chambers to prevent brake lock-up. Only the rear axle is equipped with an ABS system.

2.3.2 New Flyer 60' Diesel

The New Flyer 60' diesel bus is equipped with a similar S-cam pneumatic brake system, comparable to that on the New Flyer 40'. The on-board air supply is from an engine-driven Bendix TU-FLO 750 air compressor running at engine speed (
Figure 8.10 in Appendix B). The air system is controlled by a governor. When air pressure in the wet tank is below 105 psi, a signal is sent to the governor to close the valve in the dryer and start compressing air into the system. ABS systems are installed on front, center and rear axles.

2.3.3 Gillig 40' Low Floor

Similar to the New Flyer 40' CNG bus, the Gillig 40' low floor bus is equipped with S-cam pneumatic brake system as shown in (Figure 8.11 in Appendix B). Both axles are equipped with an ABS system as shown in (Figure 8.12)

2.3.4 VanHool 40'

The VanHool 40' bus is equipped with D-Elsa compressed air disk brakes manufactured by Lucas. ABS is installed on both front and rear axles. In addition to the ABS system, traction control such as ASR is also installed. Figure 8.13 shows the location of ABS valves and ASR valves.

2.3.5 Summary

All the buses investigated are without the centralized electronic control of an electronic brake system (EBS). Therefore, actuating the pneumatic brake system through existing in-vehicle components is not possible. Rather, it is necessary to make more significant modifications to the existing pneumatic brake system in order to implement a brake actuator.

2.4 Engine/Transmission

The engine performs the conversion of heat energy generated from fuel burning to mechanical torque at the drive shaft. Compressed natural gas (CNG) and diesel fuel are the most popular fuels used in bus engines, and these engines have significantly different operating characteristics. To provide a wide range of torque and motion combinations to suit different driving conditions, the engine torque and rotation are transmitted to the driving wheels of the bus through a variable speed transmission.

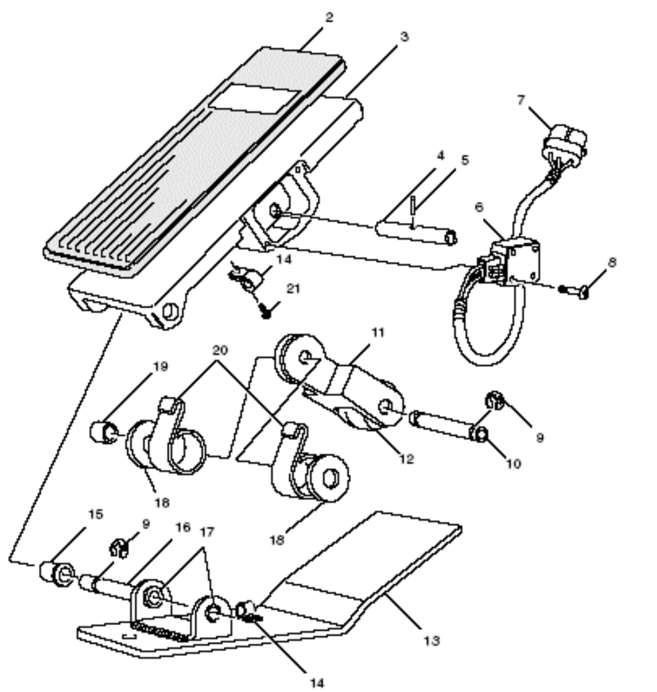
If longitudinal speed control or longitudinal precision stopping is required for the VAA system, propulsion actuation is needed to actuate the bus's existing engine/transmission to deliver the desired driving force. The characteristics of the engine and transmission must be well understood before the propulsion controller can be designed, in order to make sure that the speed and acceleration of the bus can be controlled smoothly and accurately. The smoothness and accuracy are needed for passenger comfort, fuel economy, minimizing emissions and ensuring safety of the control of the bus motions.

2.4.1 New Flyer 40' CNG

The New Flyer 40' CNG bus is equipped with a Cummins C8.3G CNG engine. The Cummins C8.3G CNG engine is an 8.3 liter, four-stroke, inline, high speed engine. The electronic fueling control system consists of two separate systems: the electronic control module (ECM) and governor control module (GCM).

A standard electronic accelerator pedal containing a pedal position sensor and idle validation switch (as shown in Figure 2.7) is installed to provide inputs to the engine GCM.

The transmission system consists of an Allison B400R transmission, an electronic controller unit (ECU), the shift selector located on the instrument panel, and a remotely mounted transmission cooler and accumulator. The ECU receives control inputs from the shift selector and inputs from the sensors in the transmission control module. It processes this information and sends shift commands to the control module. The ECU also provides diagnostic information which can be read as codes through the shift selector or downloaded using a data reader.



1. Accelerator Assembly, Electronic (Incl. 2..21)
2. Cover
3. Treadle
4. Shaft, Sensor Drive
5. Pin, Spring
6. Potentiometer
7. Wire Harness
8. Screw
9. Snap Ring, Truarc
10. Roller Pin
11. Lever, Treadle
12. Roller
13. Base Plate, 45°
14. Clamp, Wire Blk.
15. Bushing
16. Pin, Treadle
17. Bushing
18. Washer, Thrust Outer
19. Bushing, Garlock
20. Spring
21. Screw, Pan #8 - 32 UNC x 5/16"

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Figure 2.7 Accelerator Pedal Assembly

2.4.2 New Flyer 60' Diesel

The New Flyer 60' diesel bus is equipped with a Series 50 high speed diesel engine manufactured by Detroit Diesel. The engine-mounted ECM includes control logic to provide overall engine management. The ECM continuously performs self diagnostic checks and monitors the other system components. An electronic accelerator pedal similar to that in Figure 2.7 provides the engine ECM with throttle input. The transmission system is an Allison B500R which is similar to the one used in the 40 foot CNG bus.

2.4.3 Gillig 40' Low Floor

The Gillig 40' low floor bus is equipped with a Detroit Diesel Series 50 diesel engine, which is the same as the New Flyer 60' diesel. An electronically controlled fueling system is installed. The electronic fueling system uses an accelerator pedal with an internal potentiometer to regulate the flow of fuel to the engine. The same transmission (Allison B400) as that used in the New Flyer 40' CNG bus is installed on the Gillig 40' low floor diesel bus. Details can be referred to the corresponding section on the New Flyer 40' CNG bus

2.4.4 VanHool 40'

The VanHool 40' bus is equipped with a Cummins ISL diesel engine. The accelerator pedal is connected to the engine fuel injection pump by electric wiring. The electronic controller unit calculates the desired injected quantity and injection timing for every operating condition. This results in a reduction of the pollutant emissions and offers an exceptionally high torque at low engine speeds. The electronic controller unit also monitors the operation of the engine-control system. When a failure is detected, the electronic controller unit limits the engine speed and power, and will shut off the engine after approximately 30 seconds. A Voith 864.3 E automatic transmission with hydraulic retarder is installed.

2.4.5 Summary

Most of today's heavy duty vehicle engine/transmissions are equipped with sophisticated electronic controls. It is very difficult to modify the internal controls of the engine/transmission to implement the propulsion actuator design, because these are proprietary to the manufacturers and are carefully tailored to the specific characteristics of the individual engine/transmission. From the propulsion actuator design point of view, it is important to note that most of the engine/transmissions are "throttle-by-wire" systems, using an electronic accelerator pedal. This makes it easy to provide the propulsion actuation function through an electronic interface with the VAA control computer, regardless of whether the vehicle is equipped with its own internal network.

2.5 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 desirable to use components that are already compatible with the standard onboard electrical power characteristics of transit buses.

2.5.1 New Flyer 40' CNG and 60' Diesel

The electrical system is a 12/24 VDC split system, negatively grounded. All components are rated at 12 or 24 Volts DC, depending on the system in which they are employed. A PLC (Programmable Logic Controller) manufactured by Allen-Bradley is used for logical controls.

2.5.2 Gillig 40' Low Floor

The Gillig 40' low floor diesel bus has a dual electrical system composed of both 12V and 24V DC power. The Dinex-MPX multiplex system (a control system similar to PLC) made by I/O Controls Corporation is used to handle logical controls like interlocking of door open/close, low air warning, etc.

2.6 CAN In-Vehicle Network System

The Controller Area Network (CAN) is a serial communication protocol which efficiently supports distributed real-time control with a very high level of security. CAN was originally developed by the German company Robert Bosch for use in the car industry to provide a cost-effective communications bus for in-car electronics and as alternative to expensive and cumbersome wiring harnesses. The car industry continues to use CAN for an increasing number of applications, but 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 CSMA/AMP (Carrier Sense Multiple Access / Arbitration by Message Priority) 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 SAE (Society of Automotive Engineers) 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 in-vehicle network characteristics are very important to the functionality of VAA systems for two major reasons. First, the VAA system could tap into the in-vehicle network to acquire sensor information that is already available on the network. Second, the in-vehicle network provides a simple channel for the VAA system to actuate the existing vehicle's engine/transmission or brake system if the system configuration allows. Therefore, understanding the existing in-vehicle networks and integrating the existing in-vehicle networks into VAA systems could make it possible to simplify VAA system design and save the cost of additional sensors.

2.6.1 New Flyer 40' CNG

The New Flyer 40' CNG bus has a Cummins C8.36+ CM556 electronic control system, which features both the J1587 (a slower serial data communications link standard which uses RS-485 transceivers and receivers) and J1939 serial networks (Figure 2.8, based on CAN networks). The transmission, engine and braking system ECMs are all connected together by both the J1939 and the J1587 serial networks. The J1939 network on this system is configured for a communication bandwidth of 250Kbps. The engine ECM is not calibrated to respond to the J1939 Torque/Speed Control message, and no engine retarder is available. The ABS braking system on the 40 foot CNG bus is without the centralized electronic control of an electronic brake system (EBS). Thus the brake system cannot be controlled via the J1939 network. The detailed J1939 network messages useful for VAA system can be found in Appendix A.

2.6.2 New Flyer 60' Diesel

In the New Flyer 60' diesel bus, transmission, engine and braking systems are all connected by both J1587 and J1939 networks. The New Flyer 60' 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 ABS braking systems on the 60 foot articulated bus are without the centralized electronic control of an EBS system. 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 B.

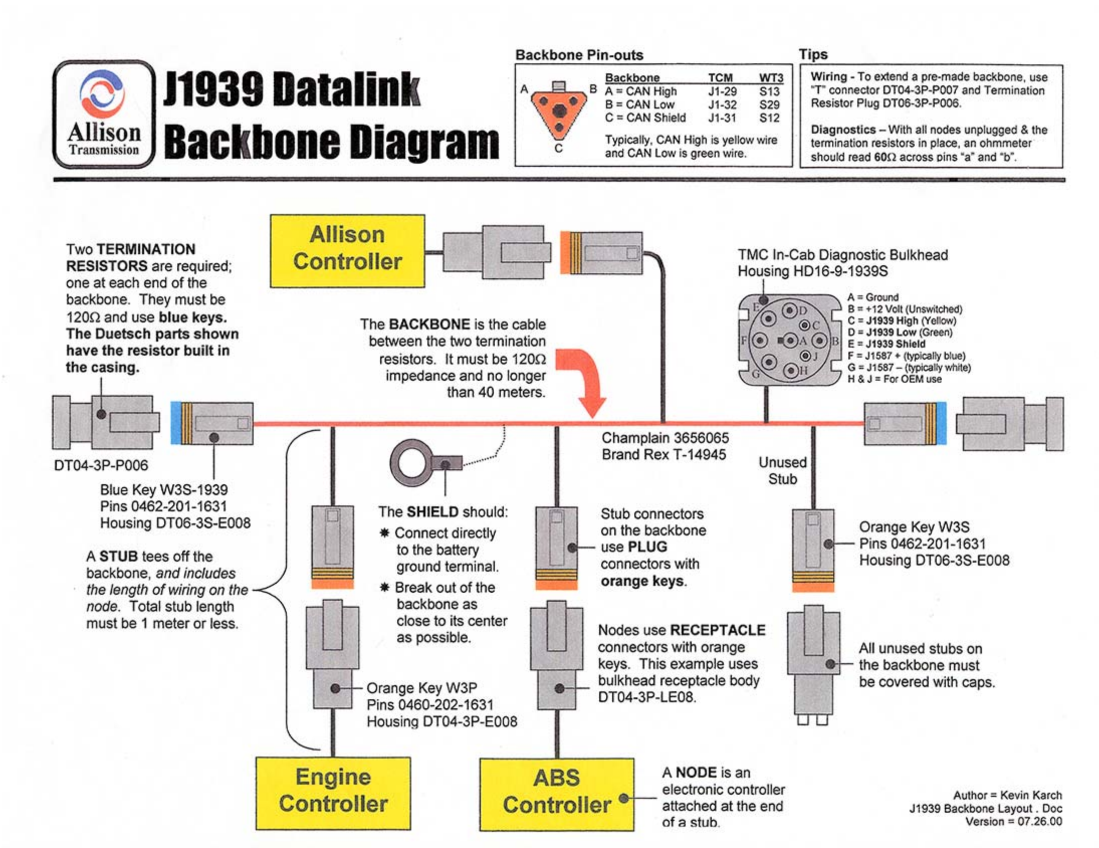


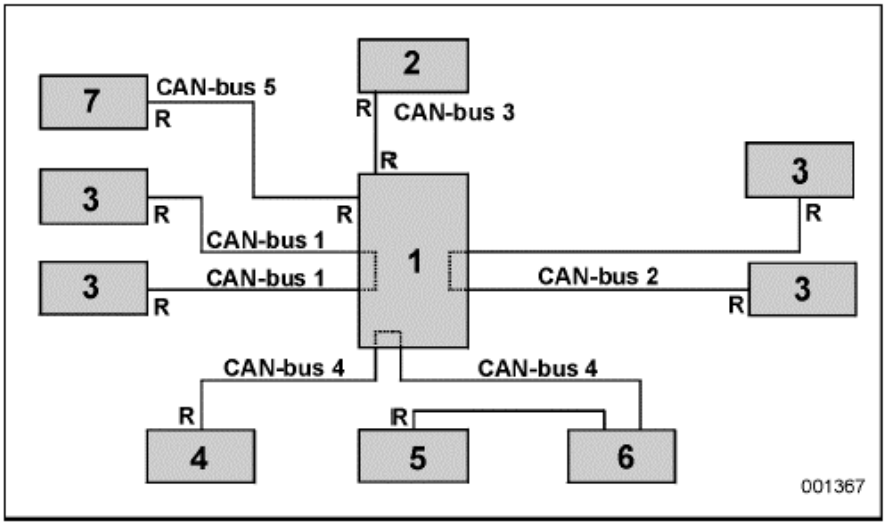
Figure 2.8 J1939 Bus Hardware Interface

2.6.3 VanHool 40’

The VanHool bus uses a KIBES multiplex system. The vehicle network is composed of 5 CAN buses which connect dashboard, transmission ECU, door controls, ABS/ASR and engine ECU (Figure 2.9). A central computer node serves as both bus gateway between different CAN buses and logic control unit. The messages are compatible with the J1939 standard.

2.6.4 Summary

With the increasing complexity of onboard electronics, the in-vehicle communication network becomes more important. Although the SAE J1939 standard was developed to serve as the in-vehicle communication network for heavy-duty vehicles, the exact information available from the in-vehicle communication network can vary significantly for different vehicles. Furthermore, the configuration of different transit buses’ subsystems is also different with respect to the in-vehicle communication network. For example, the engine of the New Flyer 60’ Diesel bus is configured to react to commands from the in-vehicle communication network, while the engine of the New Flyer 40' CNG bus does not respond to commands from the in-vehicle communication network. This diversity of characteristics will require diversity in the designs of the VAA systems for different buses.



1 Computer module
2 Dashboard node
3 Node
4 Vehicle engine control unit
5 Gearbox control unit
6 ABS/ASR control unit
7 Door controls
R Terminating resistance

Figure 2.9 Vehicle Network Configuration for VanHool 40'

2.7 Exterior Geometry

To take advantage of the precision docking function of VAA, the bus exterior geometry design has to be subjected to certain design constraints. These are important in order to ensure that the bus can approach close enough to the loading platforms at the bus stations without encountering mechanical interference between any parts of the bus and the platforms or curbs. An investigation of current bus exterior geometry designs and their implications for close approach to loading platforms is an important first step toward the development of requirement for bus exterior geometry.

2.7.1 New Flyer 40' CNG

As shown in
Figure 2.10, the New Flyer 40' CNG bus body includes a raised rubber wheel fender around each wheel. Since these wheel fenders define the outside perimeter of the bus and the actual door step

of the existing design are within the vertical plane of the bus outside perimeter, a large gap between the door step and the curb will be created when the bus docks at a station. It is recommended that modification be made to extend the door step so that the edges of the door extension (Figure 2.11) can be aligned with the outermost perimeter of the bus body, to the extent this can be done without violating legal limitations on the bus width.

Figure 2.10 Exterior of New Flyer 40' CNG Bus (with door extension)

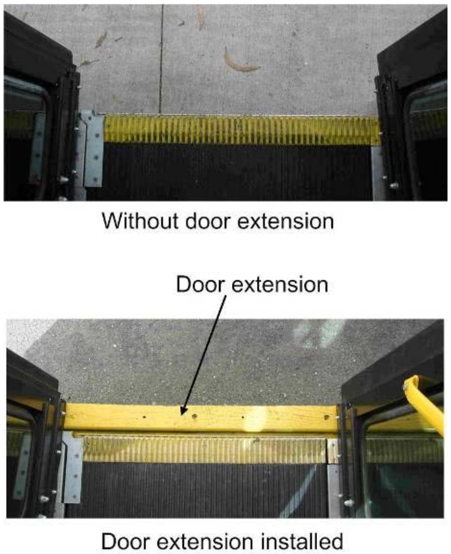


Figure 2.11 New Flyer 40' CNG Bus Door

2.7.2 New Flyer 60' Diesel

Figure 2.12 shows the exterior of the New Flyer 60' diesel articulated bus. Similar to the New Flyer 40' CNG bus, the raised rubber wheel fender (as in

Figure 2.12) and inward door step will create a large gap when the bus docks at a station.

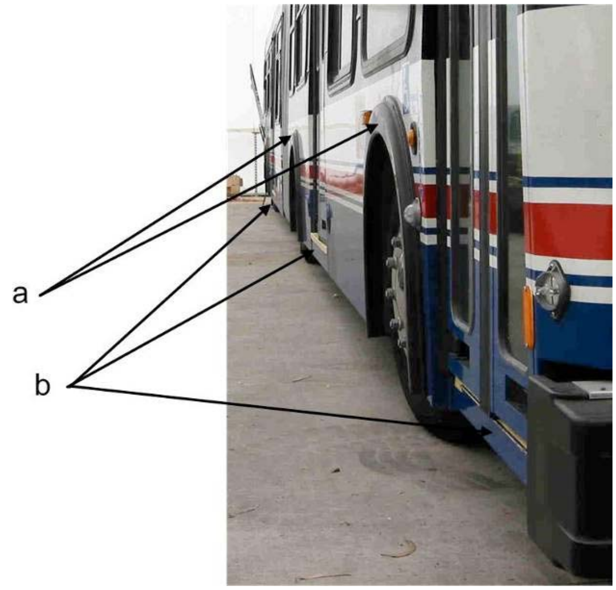


Figure 2.12 Exterior of New Flyer 60' Diesel

2.7.3 Gillig 40' Low Floor

As shown in

Figure 2.13, a similar raised rubber wheel fender appears on the Gillig bus, which is likely to create a large gap when the bus docks at the station.

Figure 2.13 Exterior of Gillig 40' Diesel

2.7.4 VanHool 40' and 60'

The exteriors of the VanHool buses are very clean designed and well suited for the precision docking function (Figure 2.14). One of minor problems is the opening of the bus's middle door. When it is opening, the door moves toward the outside first and then slides aside as shown in Figure 2.15. If docking precisely at the platform, the rubber seal at the bottom of the door will be stuck between the boarding platform and vehicle body, thereby stopping the opening of the middle door.

Figure 2.14 Exteriors of VanHool 40' (left) and 60' (right)

Figure 2.15 Opening of VanHool Middle Door

2.7.5 Summary

Most of today's buses' exterior designs are not ready for precision docking. New designs or at least some cosmetic changes are needed in order to ensure that the buses are able to approach the docking platforms and open and close their doors without interfering with the platform.

2.8 Conclusions and Findings

Table 2.2 presents a summary of the key findings from the review of the VAA-relevant characteristics of existing transit buses. The fundamental conclusions from this review are:

- The designs of basic bus subsystems such as power steering, engine/transmission, pneumatic brake system and in-vehicle network are quite mature and similar for the buses from the different bus manufacturers.
- Although the designs of subsystems are similar, the characteristics of each specific subsystem are quite different (e.g. the characteristics of power steering system, the available information from in-vehicle communication network and the capability of actuating existing vehicle subsystems through the in-vehicle communication network). To deal with such broad diversity, VAA system designs have to be flexible.
- None of the buses investigated is completely suitable and ready for implementation of the VAA system application. Some of the existing subsystems (e.g. brake system and exterior geometry) will need modifications to adapt to the VAA system application needs.

Table 2.2 Summary of existing transit bus sub-systems

	New Flyer 40' CNG	New Flyer 60' Diesel	Gillig 40' Low floor	VanHool 40'	VanHool 60'
Power steering	steering feel is heavy and large freeplay	steering feel is heavy and large freeplay	light steering feel and small freeplay	light steering feel and small freeplay	light steering feel and small freeplay. Trailer wheel steers with front wheel
Pneumatic brake system	No central EBS, S-Cam brake, ABS on rear axle	No central EBS, S-Cam brake, ABS on front, center and rear axle	No central EBS, S-Cam brake, ABS on front and rear axle	No central EBS, S-Cam brake, ABS on front and rear axle, ASR also installed	N/A
Engine/Transmission	CNG Engine with electronic accelerator pedal, Automatic transmission	Diesel Engine with electronic accelerator pedal, Automatic transmission	Diesel Engine with electronic accelerator pedal, Automatic transmission	Diesel Engine with electronic accelerator pedal, Automatic transmission	N/A
Electrical Power System	12/24V mixed system	12/24V mixed system	12/24V mixed system	12/24V mixed system	N/A
CAN bus	Detailed message list available. Engine doesnot respond to CAN bus command	Detailed message list available. Engine responds to CAN bus command	N/A	Separated bus configuration for high speed and low speed communication	N/A
Exterior Geometry	Raised rubber wheel fender. Door step falls inside bus	Raised rubber wheel fender. Door step falls inside bus	Raised rubber wheel fender. Door step falls inside bus	Door openning interferes with docking	Door openning interferes with docking

3.0 Infrastructure/Vehicle Interface Characteristics

VAA systems involve close interaction between vehicles and the infrastructure, so the interfaces between the vehicles and infrastructure are critically important to the successful design and implementation of VAA systems. The scope of this project is focused on definition of interfaces, so when infrastructure issues are discussed, specific attention is given to addressing the interfaces with the vehicles providing VAA services, rather than the much broader issues of infrastructure design. There are two primary aspects of these interfaces to consider. First, modifications of existing infrastructure designs such as running way and station platforms are required to take full advantage of VAA functionalities. Second, accurate and robust determination of vehicle position with respect to lane center is critical to VAA system performance, and must depend on one or another form of infrastructure-based reference support.

3.1 Objectives and Procedure

The roadway and bus stops may need to be constructed or modified based on VAA requirements, the chosen technology, and selected services. These construction requirements may include the strength distribution of the pavement, the smoothness of the curvature and its transition characteristics, the accuracy of the width of the roadway, as well as the smoothness and the precision of the bus stop locations. The requirements may be site dependent and need to be determined in the deployment phase. These are generally not mandatory prerequisites for the use of VAA systems, but they can significantly affect the effectiveness of the systems in practice.

Depending on the technology choice for the specific VAA system, certain infrastructure references (specific lane marking or striping, magnetic markers, wires, mechanical guide, electronic map, or differential GPS signals) are needed to support the specific sensing system. 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. Installation requirements such as accuracy and smoothness will need to be determined to ensure the performance of the guidance system as a whole.

In this chapter, vehicle-infrastructure interface requirements will be covered in areas such as running way design, station design, infrastructure-based reference and vehicle exterior geometry. The analyses are based on vehicle kinematics and PATH's prior experience in the development and implementation of experimental VAA systems.

3.2 Influence on Running Way Design

Running way design has a direct influence on the ability of VAA systems to provide benefits such as promoting a rail-like image or allowing vehicles to operate in narrower lanes. While a rail-like image could be achieved through other design elements, enabling buses to operate in narrow lanes requires the use of vehicle assist technologies. Buses equipped with VAA systems could operate on narrower lanes than a normal bus can tolerate. The minimum running way width is determined by the following factors:

- Bus width: Obviously, the width of running way has to be larger than the bus width.
- Tracking accuracy: The lateral position tracking accuracy of the VAA system determines how accurately the bus could operate within the designated lane boundary.
- Design factor: The design factor has to be determined by the system designer based on the system reliability, operational speeds, the effectiveness of the fault management system and environmental conditions such as weather.
- Minimum clearance: Minimum clearance defines the required lateral clearance between the side of the bus and the lane boundary. This may need to include allowance for a "shying distance" to accommodate the responses of drivers of vehicles traveling in the opposite direction in adjacent lanes
- Curvature offset: As explained in Section 8.3 "Effects of Tight Turning Radii on Needed Lane Width," the sharper the curve and the longer the vehicle wheelbase, the wider the lane needs to be in curves.   The curvature offset can be determined using the same equation as that for the offset tracking in Section 8.3 if the bus does not have rear-wheel steering.

The minimum lane width needed on relatively straight sections of running way is the sum of the following factors:

Bus width +
Design factor * (tracking accuracy + minimum clearance) * 2

The following example illustrates the calculation of minimum lane width. For a 7.62 cm (0.25 ft) VAA system tracking accuracy, 2.59 m (8.5 ft) bus width, 7.62 cm (0.25 ft) minimum clearance, straight road, and design factor of 2, the resultant lane width would be 3.2 m (10.5 ft).

Other issues involving running way design include:

- Strength distribution of pavement: Buses equipped with VAA systems follow their trajectory with high accuracy and repeatability. A rail-like pavement (*i.e.*, two narrow pavements located under the tires of the bus) may be preferred for the pavement design, but this pavement will have to be designed for more concentrated loading than conventional pavements.
- Smoothness of the curvature and its transition characteristics: Since the VAA bus follows the predetermined trajectory closely; the smoothness of the curvature and its transition characteristics will contribute significantly to the smoothness of bus motion and passenger comfort. The curves and their transition spirals therefore need to be defined precisely based on the levels of lateral acceleration and jerk that correspond to the desired passenger ride quality.

3.3 Influence on Station Design

Traditional station designs need to be modified to accommodate the requirements of precision docking. The influence of precision docking on the station design can be summarized as follows:

- Boarding platform geometric constraint:
  - Boarding platform height: According to the Americans with Disability Act (ADA) requirements, the vertical gap between vehicle floor and station floor shall be within plus and minus 1.58 cm (5/8 in). Most modern buses are equipped with air suspensions, so the bus height may change due to load variations. Therefore, such a stringent requirement may not be realistic for the bus docking design, especially when combined with the effects of a crowned road surface.
  - Boarding platform orientation: Another consideration for the boarding platform is the bus alignment when stopped. Due to the constraints of bus kinematics, it is very difficult to align both the front bus door and rear bus door to a straight boarding platform simultaneously, with the same lateral gap for S-curve docking (docking involving a lane change), especially for buses with longer wheelbases, such as articulated buses. This inevitably creates a larger lateral gap at the rear door when S-curve docking is performed. To solve this problem, the boarding platform should be designed to tilt toward the bus rear door.
- Entrance/exit running way design:
  - Entrance running way design: To align both front bus door and rear bus door simultaneously to the boarding platform with the same lateral gap, a straight entrance running design is required for the in-line docking scenario. The length of straight entrance running way is determined by the wheel base of the bus and the performance of the VAA system. For the S-curve docking scenario, a "swing-in" curved road can be designed before the bus docks to the platform.
  - Exit running way design: Attention should also be paid to the design of the departure curve for articulated buses with trailer wheel steering. The initial departure angle should not be too large so that it does not trigger trailer wheel steering and rear wheel will not touch curb. The exit path also needs to account for the overhang of the rear of the bus body behind the rear axle, and its potential to swing wider than the rear wheel trajectory.

In summary, the two most important design elements for stations using precision docking are:

1) the vehicle floor height and boarding platform floor height need to be equal
2) the entrance/exit running way needs to be as straight as possible

3.4 Vehicle Exterior Geometry Design Constraints

As shown in Section 2.7, traditional bus body design usually includes raised rubber wheel fenders around each wheel. Since these raised rubber fenders define the outside perimeter of the bus and the actual door step may be inboard of the vertical plane of the bus' outside perimeter, a gap between the door step and the curb may be created when the bus docks at a station. It is recommended that in this case modifications be made to extend the doorstep so that the edges of the door extension can be aligned with the outermost perimeter of the bus body, subject to legal constraints on the total vehicle width. If wheel fenders extend beyond this width, they should be truncated at the level of the loading platform in order to avoid interference. Bus doors should be designed that they can still open without interference when docking at a platform that is at the same height as the bus floor.

3.5 Infrastructure-Based Lane Tracking References for VAA

Determining the vehicle's lateral deviation relative to the lane center with high accuracy, high bandwidth and robustness is very important to the successful implementation of electronic guidance/assist systems. All lateral guidance technologies require infrastructure-based reference support of one type or another. The specific requirements for the infrastructure-based references are determined by the selected sensing technology.

- ***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. If discrete magnetic markers are used, the distance between magnetic markers cannot be too long; one meter apart is a good start for precision docking applications. Magnetic markers, if not installed properly (e.g., buried too deep below the road surface, or not perpendicular to the road surface), may increase the noise effect on lateral position estimation.
- ***GPS reference system***: To meet the vehicle position sensing accuracy requirement of the VAA system, the differential GPS technique is usually employed. The differential correction signal can be made available through several different avenues. Base stations can be established in the interested area and the differential correction signal is then broadcast through a radio link with added infrastructure cost. The location of the base station should be optimized for the signal availability throughout the bus route. The differential correction signal can also be available through the Satellite Based Augmentation System (SBAS) (e.g. paid services such as StarFire and OmniStar) and web-based Virtual Reference Station (VRS). Digital maps are also 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.
- ***Vision reference system***: The markings painted on the road surface for the vision sensing system must be visible with sufficient contrast under all intended operating conditions and able to last under the ambient environmental conditions with a reasonable investment in maintenance.

3.6 Conclusions and Findings

This chapter has addressed the interactions between the vehicle and infrastructure designs, and in particular the ways in which infrastructure designs need to be adapted to support VAA implementation. The primary issues for the infrastructure are:

- Running way: The main influence on running way design is focused on the running way width, which can potentially be reduced significantly below 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.
- 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.
- Infrastructure-based lane tracking references: Infrastructure-based references are integral parts of the most important VAA subsystem: vehicle and lane position sensing. All lateral guidance technologies require the support of infrastructure-based reference information in one form or another. The differing requirements on the infrastructure-based references are discussed for the primary existing lateral guidance technologies.

4.0 Vehicle Interface Requirements

VAA systems are composed of add-on functional units interacting with the basic bus subsystems normally controlled by the bus driver. Specifically,

- The VAA lateral control system will interact with the steering system;
- The VAA longitudinal control will interact with the engine/transmission system and the pneumatic braking system;
- The VAA system may need to take data from and send data to the existing data bus;
- Electronics for the VAA system will need to be powered by the bus electrical system.

The objective is to ensure that VAA systems designed with different technologies can interface seamlessly with buses manufactured by different bus manufacturers. Through the review of vehicle and infrastructure elements, it is evident that buses in North America use components from different suppliers, and therefore have discrepancies in respective designs. However, it was found that common vehicle interfaces can be defined for VAA subsystems to interact with the existing bus subsystems. This important finding establishes the foundation for a standard set of interface requirements that can be adopted by all manufacturers.

In order to define the VAA interface requirements, it is necessary to establish a VAA architecture through which the interface between VAA subsystems and other bus subsystems can be clearly identified. This VAA architecture needs to be modular such that interactions between VAA subsystems and other bus subsystems are streamlined. These interfaces can be defined to support all VAA performance requirements, without becoming unnecessarily complicated or burdensome. Based on the VAA architecture, interactions between the VAA subsystems and existing bus subsystems are analyzed. Following this design philosophy, the following design steps are taken in order to develop the VAA interface requirements:

i. A modular VAA system architecture is defined. The interfaces between VAA subsystems and existing vehicle subsystems are identified.

ii. The interfaces are classified into three categories -- mechanical interface, power supply, and data communication. The general design philosophy is then introduced.

iii. Data communication is more challenging than the other two interface categories. Therefore, an introduction to data communication is presented and the shared in-vehicle network is introduced in detail as the backbone of the modular system architecture.

iv. 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.

4.1 *Vehicle System Architecture*

4.1.1 Functional Blocks and Information Flows

As the first step of system design, the VAA system is partitioned into several functional blocks. Detailed analysis will be presented to show how the functional blocks interact with each other and how they interact with the existing bus subsystems. Figure 4.1 shows the schematic of a VAA system, organized by functional blocks, with information flows shown between functional blocks and its 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.
  - **Vehicle state sensing**: The components in this category potentially consist of existing or additional vehicle sensors. The vehicle state information includes vehicle speed, engine speed, gear position 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 boundary. It is the key sensor in the VAA-PD and VAA-VG systems. Vehicle position sensing systems using computer vision, magnetic sensing, mechanical contact and Global Positioning System (GPS) sensing all require infrastructure support of some sort.
  - **Communication**: Communication includes vehicle-to-vehicle communication (e.g. to support VAA functions such as platooning) and roadside-to-vehicle communication (e.g. acquisition of differential signals for Differential GPS).

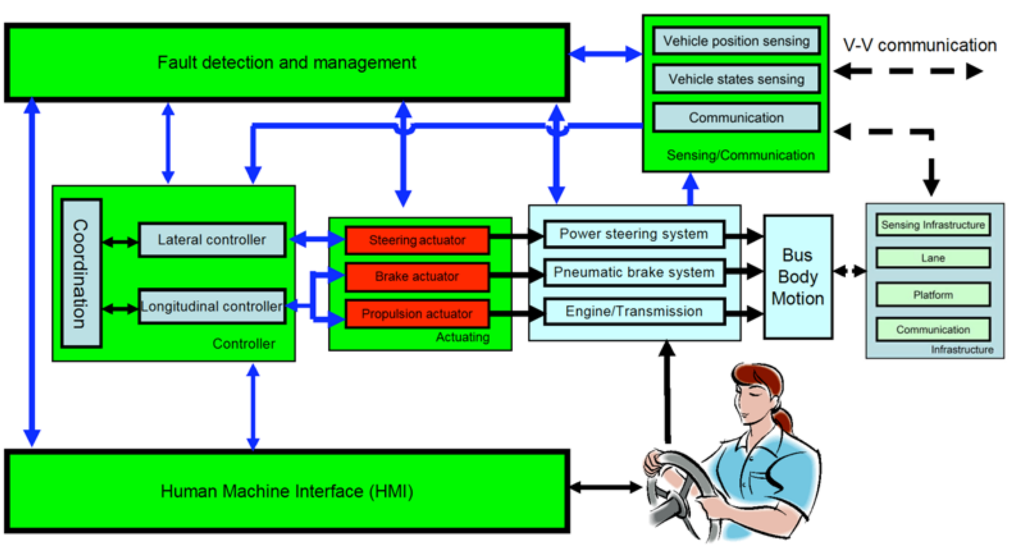


Figure 4.1 VAA System Functional Blocks and Information Flows

- ***Actuating***: Actuating directly interfaces with the bus's power steering system, pneumatic brake system and engine/transmission to provide steering, driving and braking force for the desired vehicle maneuvers.
  - **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.
  - **Brake actuator**: The brake actuator receives control commands from an upper level controller and actuates the existing bus's pneumatic brake system to provide desired braking force.
  - **Propulsion actuator**: The propulsion actuator receives control commands from an upper level controller and actuates the existing engine/transmission to provide the desired driving force.

- ***Controller***: The controller is the brain of the VAA system. It receives commands from the driver through the Human Machine Interface (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.
  - **Longitudinal controller**: The longitudinal controller calculates the braking and propulsion commands sent to the brake and propulsion actuators so that the bus maintains the desired speed or stops at the exact location for precision docking.
  - **Coordination controller**: The coordination controller issues commands to both lateral controller and longitudinal controller 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 but 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. Installing a VAA system may include lane construction, sensing infrastructure installation, platform construction and roadside communication link**.**

Generally, the VAA system operates as follows:

- The sensing/communication block obtains information such as vehicle lane position and related vehicle states (e.g. vehicle speed, brake pressure etc) from its interactions with sensing infrastructure, data communication with existing bus subsystems, other VAA subsystems and wireless communication with other buses and the roadside .
- The acquired sensing information is made available to the controller, HMI and fault management subsystems through data communication.
- Once the controller receives such information, control commands (such as steering, propulsion and braking) will be calculated and sent to the corresponding actuators.
- The actuators actuate existing bus subsystems such as power steering system, engine/transmission and pneumatic brake system according to the received commands so that the desired vehicle maneuver (e.g. lane keeping with certain cruising speed and precision docking) is achieved.
- The bus driver monitors and controls the VAA system activation through the HMI.

In Figure 4.1, the green blocks indicate VAA subsystems onboard the bus. These blocks exchange information through data communication. The light blue block at the right of Figure 4.1 represents the interface to the infrastructure, which is discussed in Section 3.0.

4.1.2 System Architecture Design

The goal of system architecture design is to provide an architecture that can incorporate different VAA technologies and interface with different existing bus subsystems without fundamental changes. In this section, the advantages of a modular system architecture connected by a shared in-vehicle network are discussed first, followed by introduction of the recommended VAA system architecture.

Compared with centralized system architecture, a modular system architecture with a shared network has important advantages. Today's vehicles contain hundreds of circuits and sensors, and many other electrical components. Communication is needed among the many circuits and functions of the vehicle. In early vehicle systems this type of communication was handled via a dedicated wire through point-to-point connections. If all possible combinations of switches, sensors, motors, and other electrical devices are accumulated, the resulting number of connections and amount of dedicated wiring would be enormous. A modular system architecture with a shared communication network provides a cheaper, safer, more reliable and efficient solution for today's complex vehicle systems.

In-vehicle networking, also known as multiplexing, is a method for transferring data among distributed electronic modules via a shared data bus. Without shared in-vehicle networking, inter-module communication would require dedicated, point-to-point wiring, resulting in bulky, expensive, complex, and difficult to install wiring harnesses. Applying a shared data bus reduces the number of wires by combining the signals on a shared data bus through time division multiplexing. Information is sent to individual control modules that control each function, such as anti-lock braking, turn signals, and dashboard displays.

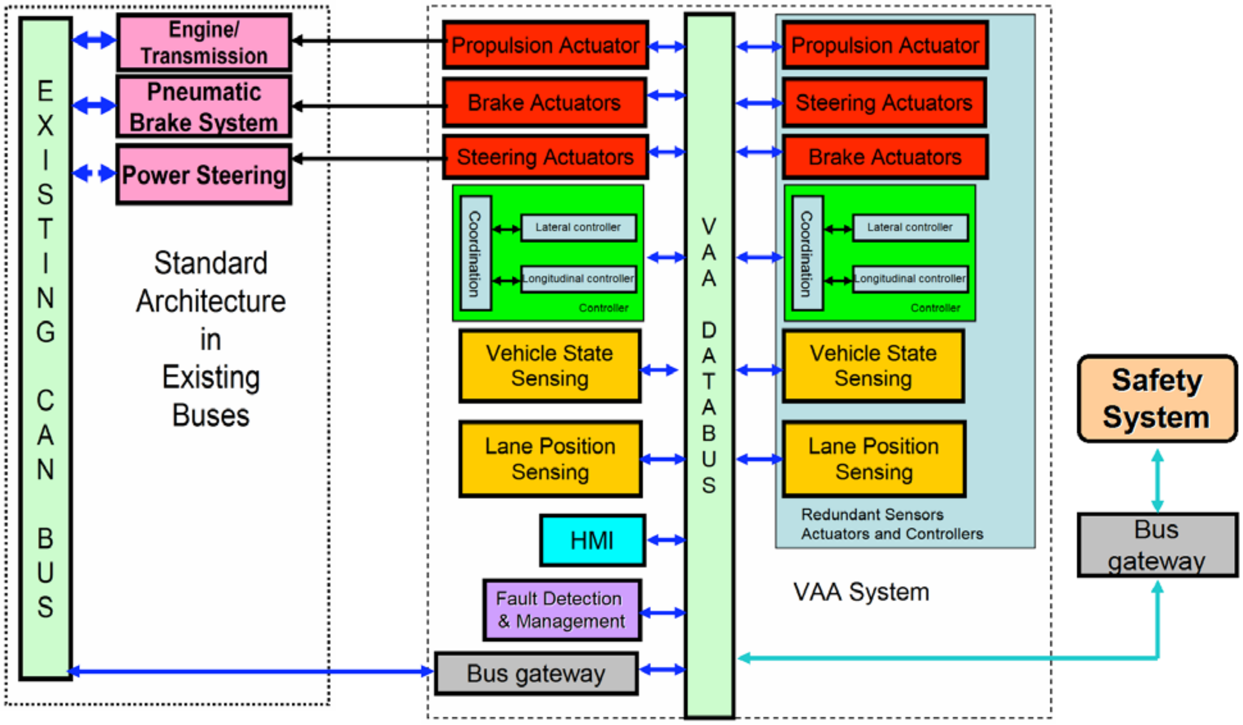


Figure 4.2 VAA System: A Modular Distributed System Architecture

As shown at the left side of Figure 4.2, a modular system architecture with shared in-vehicle network has already become common practice in industry. For heavy duty vehicles such as trucks and buses, the SAE J1939 standard has been developed as the standard of communication protocols among electronic controller units. Standardized protocols allow modules from many suppliers to easily link together, forming a type of "open architecture". Such a flexible "open architecture" allows easy expansion of system function with additional new modules. Another trend in the vehicle system architecture is that multiple data buses are implemented in vehicles. Usually, a low speed data bus is used for locks, windows and other devices. A high speed one is used to connect devices such as engine/transmission, ABS and traction control, which are related to real time control (e.g. VanHool's in-vehicle network architecture as shown in Figure 2.9).

To comply with the common industry practice, especially for heavy-duty vehicles, the VAA system architecture is designed as a modular system connected by a dedicated VAA data bus as shown in Figure 4.2. The dedicated data bus for the VAA system is connected to the existing vehicle data bus through a bus gateway. Functional blocks such as sensing, actuators and controllers are designed as smart modules that are connected by the dedicated data bus. In order to allow modules (e.g. steering actuator and vehicle position sensing) from different suppliers with different technologies to be combined in a VAA system, interface requirements between the VAA sub-systems and existing bus sub-systems should be established. The interfaces between VAA system modules (i.e., the communication protocol for the dedicated data bus) should also be specified.

From the existing transit bus system point of view, engine/transmission, brake, power steering and existing CAN bus are the sub-systems that directly interface with the VAA system. They were already discussed in Section 2.0. From the VAA system point of view, the functional blocks that directly interface to the existing transit bus subsystems are sensing and actuating. These will be discussed in detail in the rest of Section 4, along with data communication between different functional blocks, which is an integral part of the VAA system. From the infrastructure point of view, lane construction, boarding platform and sensing infrastructure directly interface with the VAA system. They were already discussed in Section 3.0.

Based on the knowledge of the existing vehicle subsystems and infrastructure reviewed in Sections 2.0 and 3.0, the interface requirements are described here for VAA system functional blocks and existing vehicle subsystems. The objective is to provide a unified set of interface requirements to accommodate a full range of VAA system technologies and existing vehicle subsystems.

4.2 General Design Philosophy

The interfaces between the VAA system and an existing transit bus can be classified into three major categories: mechanical (including mechanical installation, hydraulic or pneumatic connections), data communication (including dedicated signal connections and in-vehicle data networking) and power supply (including electrical, hydraulic and pneumatic power). Although the exact interface requirements are subject to the specific system design, general guidelines for VAA system interface requirements are:

- 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.

4.3 Overview of In-vehicle 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 preferred as shown in Figure 4.2. In such a configuration, individual functional blocks such as sensors, actuators, HMI and controller have their own local processors. These "smart" functional blocks communicate via a common data bus 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 report is on the application layer. 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? These are the questions to be addressed here. The answers support the definition of the message framework as well as information interface requirements.

How to implement the data communication network subsystem in the lower level of the network OSI model is not the focus of this report, since this is subject to change with advances in technology. Different communication protocols have been proposed for distributed real-time control systems, especially for the safety-critical automotive applications such as X-by-wire (X means steering, braking or throttle). The Controller Area Network (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 Anti-lock Brake Systems (ABS) with bit rates up to 1Mbits/sec. 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 transit buses. J1939 has already defined messages at the vehicle application layer level for common powertrain (engine, transmission and braking) applications. The J1939 Torque/Speed Control message already provides much of the information required by the longitudinal controller. There is still a great deal of undefined message space in the J1939 standard available for use by future applications areas, one of which could be VAA. In the short term, the proprietary message space can be used to implement messages supporting VAA functionality.

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. Several different protocols (e.g. FlexRay, SAFEbus, Time Triggered CAN (TTCAN), and Time-Triggered Protocol (TTP)) have been proposed to add the time triggered communication and other functions suited for real-time control systems. However, these proposed communication protocols are not yet widely implemented in the heavy vehicle market.

4.3.1 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 heart beat 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.

4.3.2 Message Properties

- ***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 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.

4.4 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 4.3 shows a general schematic of vehicle and lane positioning sensing. The sensing device (e.g. GPS receiver, video camera or magnetometers) detects the changes (e.g. electro-magnetic wave, light or magnetic field) 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 usually installed as a complementary sensor to a GPS system to mitigate blockage situations. Different sensing technologies can also be used to complement each other in order to increase system reliability, or to allow the system to operate in environments where different infrastructure sensing support may be available on different parts of a route.

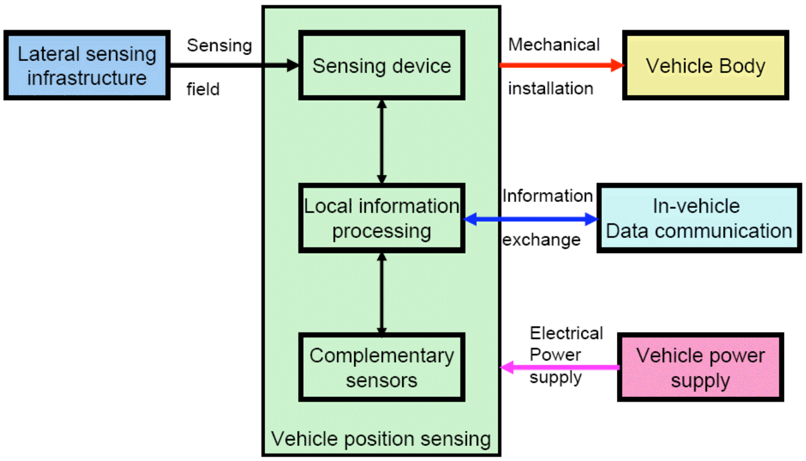


Figure 4.3 Schematic for Vehicle Position Sensing

4.4.1 Performance Requirements

4.4.1.1 Position accuracy:

The position accuracy depends on specific system configurations and application scenarios. For the guidance application, the indicated position error shall be sufficient to provide both guidance and guidance feedback to the driver in diverse operating conditions (e.g. different weather, visibility, signal blocking etc). As a rule of thumb, the sensed position accuracy should be smaller than 1/4 to 1/2 of the needed tracking accuracy.

4.4.1.2 Spatial coverage:

The spatial coverage shall cover the width of the desired operating roadway.

4.4.1.3 Update rate:

The timing and update rate of sensors and signal processing shall be sufficient for achieving the performance requirements. As a general rule, a 10 Hz update rate should be sufficient for most bus operations, since the bus fundamental dynamics generally operate below 2 Hz.

4.4.1.4 Time delay:

Although it is always preferable to have a sensing delay as short as possible, the sensing delay from input to output shall at worst be kept shorter than 0.05 seconds to allow accurate tracking of bus dynamics at the 10 Hz update rate.

4.4.1.5 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 and extreme temperature variations etc), or such factors shall be compensated.

4.4.1.6 Sensor Redundancy:

Vehicle and lane position sensing is the critical sensor for the operation of the VAA-PD and VAA-VG systems. Depending on the exact operating scenarios and system design requirements, redundant sensors may be necessary to ensure safe operation. The redundant sensor could be another sensor based on the same technology (e.g., two magnetometer bars installed at different locations under the bus) or sensors based on different technologies.

4.4.2 Mechanical Installation

Mechanically, the requirements on the installation of a sensing device on the vehicle body depend on the specific technology implemented. 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. 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.

For vision systems, the sensing infrastructure includes specially designed features painted on the road surface (e.g., white stripes). The video camera senses the light reflected by these features. To ensure a clear sight of the painted features on the road surface, the camera shall be installed on the upper part of the vehicle front.

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.

4.4.3 Electrical Power Supply

Vehicle and lane 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. 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. A power control unit is also needed to detect the main power failure and switch to the backup power supply or UPS.

4.4.4 Data Communication

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

4.4.4.1 Sensor ID:

Sensor ID gives a unique identification of the message origin for vehicle positioning sensing, especially when multiple redundant sensors are employed.

4.4.4.2 Status:

The status could be the status of the sensing block, such as ready/not ready, normal/fault and failure code. The status could also be the status of operation such as startup, shut-down and calibration. Status messages could use a slower update rate (e.g., below 1 Hz). Most status messages are important messages that need redundancy.

4.4.4.3 Health:

Health messages could be heart-beat signal or message counters embedded in the message.

4.4.4.4 Position type and related parameters:

- **Lateral position output**: The lateral position output message is a very important message for the VAA system. It is the sensing input for the lateral control system and hence requires a fast update rate (greater than 10 Hz) with high priority. The message encoding shall provide enough precision over the possible data range. Redundancy is needed for safety concerns.
- **Confidence parameter:** A confidence parameter provides information about how much trust can be placed in the lateral position output from the vehicle positioning sensing block. It could be a statistical parameter calculated by the vehicle positioning sensing block from its internal state, or an objective measure of the sensing environment (e.g., missed magnet indicator for magnet processing or ambient light meter reading for vision systems).
- **Sensor type**: Sensor type indicates the exact sensing technology of the vehicle-positioning block. It could be magnetic marker, video or GPS.
- **GPS positioning related messages**: If GPS technology is adopted, information directly from GPS such as speed-over-ground, GPS UTC time and the GPS status information (e.g. dilution of precision (DOP) and number of available satellites) shall be made available on the data communication network. Other information obtained from digital map matching (e.g. road curvature, slope and distance to the next bus stop, etc.) is also needed on the data communication network.
- **Vision positioning related messages**: If vision positioning technology is adopted, vision positioning status information such as lens condition and lighting condition shall be available on the data communication network. Other information from video image processing (e.g. road curvature) is also needed on the data communication network.
- **Magnet sensing related messages:** If magnetic sensing technology is adopted, information such as look-ahead location, position-sensing timing, coding and embedded information shall be available on the data communication network.
- **Calibration parameters**: Sensor calibration will be performed when the system is started or upon request. The related parameters include sensor location and sensor range.

4.4.4.5 System Command:

System commands include reset, calibration and change system parameters.

4.4.4.6 Other vehicle sensors or status:

Speed, yaw rate, rain sensor, ignition and power.

4.5 Vehicle State Sensing

Vehicle state information such as bus motion state (steering angle, vehicle speed and yaw rate), bus operation state (door opening) and bus driver's status (attentiveness and fatigue) can be integrated into the VAA systems to improve either efficiency or safety. Vehicle state sensing can be implemented in different ways. First, the information can be acquired from existing vehicle components through data communications. Engine and transmission ECUs constantly broadcast engine/transmission states (e.g., vehicle speed, engine speed and gear position, etc.) over an in-vehicle data network (e.g., J1939 serial bus). This information can be available to the VAA system by tapping into the in-vehicle data network. Second, some information can be shared with other functional blocks of the VAA system through data communication (e.g. steering angle from steering actuator). Finally, additional sensors can be installed to collect necessary information (e.g., an INS package for yaw rate and acceleration).

4.5.1 Performance Requirements

The exact vehicle parameters that need to be detected may vary for different applications and implementations. The following is a list of the most important vehicle parameters and their requirements.

4.5.1.1 Vehicle speed:

Vehicle speed sensing shall encompass the full range of the bus speeds, with minimum speed at least as low as 1.8 mph (0.5 m/s, the lower the better for stopping precision) and minimum update rate 10 Hz.

4.5.1.2 Yaw Rate:

Yaw rate sensors shall detect maximum yaw rate of 150 deg/sec with resolution better than 0.05 deg/sec.

4.5.1.3 Events:

All events, such as door open/close, light on/off, etc., that indicate conditions that are relevant to VAA applications, shall be converted into signals readable directly by the VAA computer or communicated from the data bus.

4.5.2 Mechanical Installation

The mechanical installation of the vehicle sensing depends on the exact implementation method and specific chosen sensing technology. For example, the INS sensors such as 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. 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.

4.5.3 Electrical Power Supply

Similar to the vehicle and lane position sensing, vehicle state sensing will 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 back up power supply or UPS, will be needed to interface with the existing vehicle electrical power system.

4.5.4 Data Communication

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

4.5.4.1 Vehicle speed:

Vehicle speed is important to both lateral and longitudinal controls. An update rate faster than 10 Hz is required, with high priority.

4.5.4.2 Yaw rate:

Yaw rate is important to lateral control and the GPS/INS integration positioning. An update rate faster than 10 Hz is required, with high priority.

4.5.4.3 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.

4.5.4.4 Engine/Transmission states:

Engine/transmission states 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.

- Engine speed
- Engine Torque
- Wheel speed
- Gear position
- Shift-in-progress
- Torque converter lock-up
- Retarder Torque

4.5.4.5 Events:

Door close/opening, lights on/off, windshield wipers on/off and speed, warning from collision warning system, etc.

4.6 Steering Actuator

The function of the steering actuator is to receive steering commands and turn the tires to the desired angle according to the commands. The steering actuator can also be used as a haptic feedback device to alert the driver in certain circumstance. It is the most important actuator for the lane keeping and precision docking functions of VAA.

The implementation of the steering actuator can vary. The steering actuator can be an add-on device attached to the existing steering system, or part of a modified steering assist system, or a separate new steering device (e.g. steering-by-wire). Figure 4.4 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, a clutch or a hydraulic bypass mechanism, which can be controlled by the local controller or outside controller, should 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 should also include components like a local processor which hosts local servo controller and local sensors for position or pressure sensing feedback.

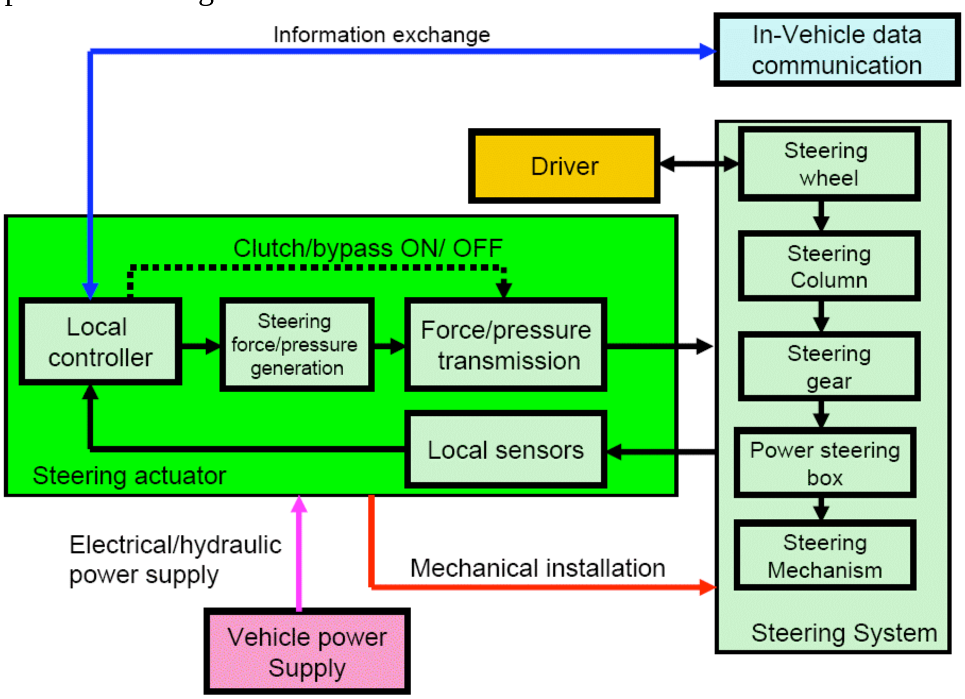


Figure 4.4 Schematic of the Steering Actuator

The actual implementation of steering actuators can be quite different from application to application. The following summarizes alternative steering actuator implementation methods.

- ***Control System Structures***: From the control system structure point of view, steering actuator implementation can be classified into the following two different methods.
  a. **Integrated design:** The control of the steering actuator can be integrated into the upper level lateral control design. Although this could make it possible to optimize the control system design in a global fashion, the integrated design increases the system complexity and the difficulty of the lateral control design.
  b. **Modular design:** The steering actuator functions as a position servo or a velocity

servo, i.e., the upper-level lateral controller sends either a steering angle command or a steering velocity command to the steering actuator. The local servo loop inside the steering actuator actuates the steering system to generate the desired steering angle or steering angle velocity. The modular design structure decouples and simplifies control system design.

- ***Torque generation methods:*** Based on how the steering actuation is generated, the steering actuator implementation can be classified into the following two methods.
  a. **Electric motor**: An electric motor has the advantages of easy installation and a linear relationship between current input and output torque. However, a large size motor in comparison to the hydraulic system and reduction gear system is needed to generate a large driving torque for the steering actuator, especially when the motor is installed closer to the tires than the power steering box.
  b. **Hydraulic power**: A hydraulic system has the advantage of its small size-to-power ratio. However, such an implementation inevitably modifies the inside of the hydraulic power steering system, which requires the participation of the power steering system manufacturer. The non-linear relationship between hydraulic pressure and flow brings in additional difficulty for control design, and the modification of the hydraulic system may impact the driver's feel of the steering operation.

- ***Torque generation unit locations:*** Based on where the steering actuation torque generation unit is located, steering actuator implementation can be classified into the following three methods.
  a. **Before power steering box (farther from tire):** If the torque generation unit is located before the power steering box, only a small torque generation unit will be needed, and it is easy for the driver to take over control when an emergency occurs. 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. The disadvantage is that such a design includes existing steering system nonlinearities into the steering actuator design. Although the size of the torque generation unit is smaller, the installation space still is limited before the power steering box. . For example, the steering actuator installed on the PATH New Flyer buses uses a DC motor to drive the steering column.
  b. **After power steering box (closer to tires):** Installing the torque generation unit close to the tires will bypass the bus power steering system. Such design requires a torque generation unit that can generate large torque or force.
  c. **Inside power steering:** Modification inside the power steering (could be either electrical or hydraulic) is another option. However, this configuration requires active participation of the power steering system manufacturer.

4.6.1 Performance Requirements

As presented in the previous section, there are a variety of implementation methods. The individual system designer can determine the steering actuator requirements as long as the resultant VAA system achieves the desired performance requirements. The following is a list of functional requirements that each system designer would need to determine and provide to the vehicle or component manufacturer, based on the system performance and the characteristics of the individual steering actuator:

4.6.1.1 Actuator Power:

The power of the steering actuator torque generation unit (electrically or hydraulically) shall be large enough to drive the steering system in all anticipated circumstances. One way to determine the power needed for the steering actuator is to conduct the experimentation as suggested in Section 2.2.4. The torque generation unit should generate force/torque large enough to overcome the tire aligning torque/force in the worst case. For better steering actuator performance, the output force/torque shall be at least two or three times the largest resistant force/torque. It is also important that the actuator power not be too large to be overtaken by the driver, and that it can be shut off automatically under emergency situations. 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).

4.6.1.2 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 should reflect this. A starting point should be 10 degree/second at the tire or 180 degrees/second at the hand wheel.

4.6.1.3 Servo performance:

If a modular design is selected, for example, a position servo, the steady state tracking error shall be within 1 degree at the hand wheel. The minimum servo loop bandwidth shall be 4 Hz for small amplitude commands (within 20 degrees at the hand wheel) at high speed (above 10 mph), and 1 Hz for small amplitude commands and low speed (from 0 to 10 mph).

4.6.1.4 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.

4.6.1.5 Steering angle sensor accuracy:

Steering angle sensor accuracy shall be within 1 degree at the hand wheel for the full steering wheel operating range (could be +/- 720 degree in hand wheel). Accuracy of 0.2 degree is preferred for the steering servo controller design.

4.6.1.6 Steering angle 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).

4.6.1.7 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 hand wheel.

4.6.1.8 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.

4.6.1.9 Actuator redundancy:

Depending on the reliability of the actuator, actuator redundancy may be required for the steering actuator. The 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 emergency backup.

4.6.2 Mechanical Installation

The mechanical installation shall satisfy space limitations. If the steering actuator is installed on the steering column, it shall not interfere with the manual steering operations of the bus driver. The installation shall not create excess hard nonlinearities like friction and freeplay. If the steering actuator is an add-on design, the hard nonlinearities (freeplay, friction etc) within the existing steering system shall be limited (less than 10 degrees at the hand wheel for the freeplay) to facilitate VAA functionality.

An electric motor-based add-on steering actuator can be installed on the steering column. As shown in Figure 2.3, Figure 2.5 and Figure 2.6, the space on the steering column is very limited. Mounting a large motor and its associated gear reduction system could easily interfere with the driver's operation of throttle and brake, and the reduction in space could make the driver uncomfortable as well. Another possible location for an electric motor based add-on steering actuator is under the floor, where the motor could be installed between the universal joint and power steering box, but in that location it would be exposed to harsher environmental conditions. In summary, the location of the steering actuator shall be chosen by the manufacturer for each specific bus model.

4.6.3 Electrical (Hydraulic) Power Supply

Depending on how the steering actuator is designed (electrical or hydraulic), the vehicle shall be able to provide enough electrical/hydraulic 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 are quite large for the steering actuator in operation, attention should also be paid to the effect of such a power surge on the remaining vehicle systems.

4.6.4 Data Communication

The messages from and to the steering actuator block are listed as follows:

4.6.4.1 Actuator ID:

Actuator ID gives unique identification of the messages sent to/from the steering actuator, especially when multiple redundant steering actuators are employed.

4.6.4.2 Actuator status:

The actuator status includes ready/not ready, start up/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.

4.6.4.3 Actuator operation state:

The actuator operation state reflects 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). Most actuator operation states are important messages that need redundancy.

4.6.4.4 Actuator controller states:

The actuator controller state reflects the current operation mode of the steering actuator controller, which can be represented by integers. It could be position servo/velocity servo/torque, soft servo/hard servo. (These refer to the servo controller gain. Soft servo means using a smaller servo controller gain, which will be easier for the driver to override. Hard servo means larger servo controller gain, which will result in a faster servo loop.). 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.

4.6.4.5 Health signal:

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

4.6.4.6 Actuator feedback states:

Actuator feedback states are continuous variables, which can be used for upper level control or fault diagnostics and management.

- **Steering angle:** Steering angles shall have accuracy better than 0.2 degrees at the hand wheel, with an update rate at least 10 Hz. Steering angle is an important message that needs redundancy.
- **Torque**: Steering torque can be used for torque modes such as haptic feedback. Update rate at least 10 Hz is required.
- **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. Update rate at least 10 Hz is required.

- **Internal variables monitored**: Some internal variables such as motor back EMF and hydraulic pressure can be used for fault diagnostics and management.

4.6.4.7 Actuator mode command:

The actuator mode command changes the operation mode of the steering actuator. It includes Manual/Auto/Transition, Startup/Reset/Calibration that could be represented by integers. Update rate is required to be at least 10 Hz. Actuator mode is an important command that needs command redundancy.

4.6.4.8 Actuator controller mode command:

The actuator controller mode command changes the operation mode of the steering actuator controller. It includes position servo/velocity servo/torque and soft servo/hard servo, which could be represented by integers. Update rate is required to be at least 10 Hz. The actuator controller mode command is an important command that needs command redundancy.

4.6.4.9 Actuator command:

Actuator command depends on the control system architecture chosen. If a modular system architecture is chosen, then the actuator command is the steering angle position command for the position servo design or the steering angle velocity command for the velocity servo design. If an integrated system architecture is chosen, the actuator command could be the voltage command or torque command to the steering actuator motor or the valve command to the hydraulic valve of the steering actuator. The actuator command needs an update rate at least 10 Hz, with high priority and message redundancy for safety.

4.7 Brake Actuator

The brake actuator receives brake control commands and "actuates" the vehicle brake system so that the desired brake force can be delivered to slow down the vehicle. Most buses are equipped with pneumatic brake systems. The right side of Figure 4.5 shows the pneumatic loop of a typical heavy-duty vehicle air brake system.

Brake actuators can be designed in many ways. Figure 4.5 shows the schematic of a general brake actuator. The braking force/pressure generation unit is the core of the brake actuator. The generated force/pressure may be inserted into the brake system through transmission line like gears or pneumatic pipes. To ensure safe operation, a bypass mechanism, which can be controlled by the local controller or outside controller, should be designed in the force/pressure transmission line to disengage the brake actuator when necessary. Local pneumatic pressure sensing or position sensing feedback is needed for the local pressure/position feedback controller. In addition, the driver must retain the ability to apply the brakes manually to provide a safety override to the automatic braking system.

In the Minnesota GPS truck project, an electrical motor was added to control the brake pedal position. This method does not modify the original brake system, but it often introduces additional dynamics and nonlinearities such as brake pedal sticking. In PATH’s Freightliner trucks, the original pneumatic brake system was outfitted with a WABCO brake-by-wire EBS (Electronic Braking System) with signal compatibility with the original ABS. The new EBS allowed WABCO-proprietary braking commands to be sent over the J1939 network. Such an EBS without pneumatic backup actuation is intended for the European market, and is not yet street-legal in the United States. In the PATH New Flyer buses, a supplemental brake actuator consisting of "off-the-shelf" pneumatic valves (e.g. proportional pneumatic valve, volume booster and double check valve) was installed to form a general "brake-by-wire" actuator similar to the WABCO EBS design, while still preserving the integrity of the original pneumatic brake system.

A transmission retarder can be used to generate limited braking force, which can be used for longitudinal speed regulation. Such braking force usually is not enough to stop the bus completely, but it can augment the force from the brakes. If the system configuration allows, the transmission retarder can be actuated through the in-vehicle communication network.

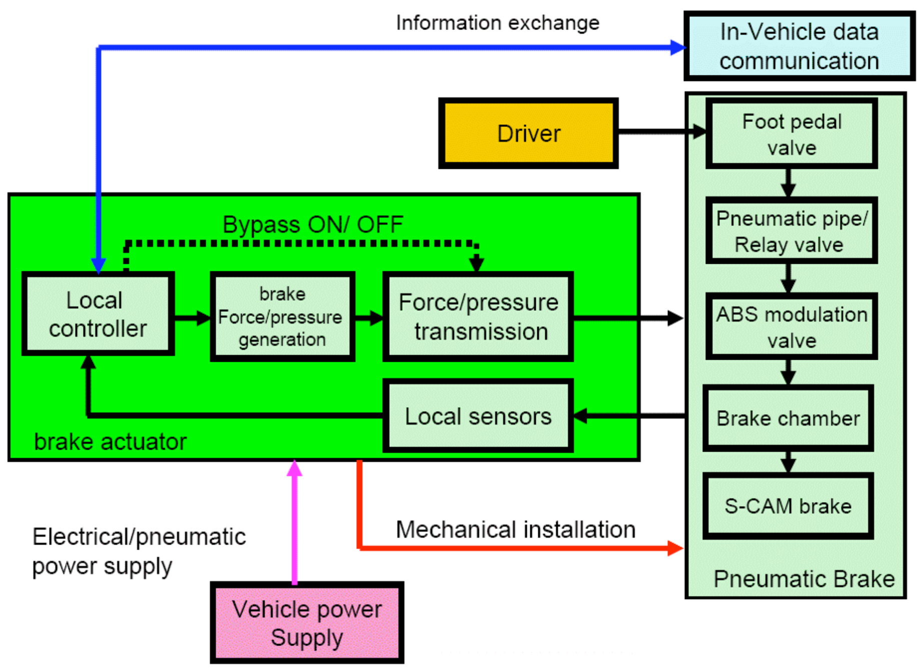


Figure 4.5 Schematic of a General Brake Actuator

The individual system designer can determine the brake actuator requirements as long as the resultant VAA system achieves the desired performance requirements, and the design shall not interfere with the manual operation of the bus driver. Whenever the driver presses the brake pedal, the pneumatic brake system shall switch to the manual-operating mode. The power of the brake actuator shall be able to stop the vehicle if the precision stopping is a desired function for precision docking. The delay between issuing the brake command and the action of the desired brake force on the vehicle shall be limited to the extent that it can be dealt with by the vehicle longitudinal controller. The exact amount of delay the system can tolerate is determined by the desired system performance and control system design.

4.7.1 Mechanical Installation

The mechanical installation shall satisfy space limitations and shall not create hard nonlinearities like friction and backlash beyond the ability of the system to control.

4.7.2 Electrical (Pneumatic) Power Supply

The vehicle shall be able to provide enough electrical/pneumatic power so that the brake actuator can generate the required brake force/pressure for the stopping operation.

4.7.3 Data Communication

The messages from and to brake actuator block are listed as follows

4.7.3.1 Actuator ID:

Actuator ID gives unique identification of the messages sent to/from the brake actuator, especially when multiple redundant brake actuators are employed.

4.7.3.2 Actuator Status:

The actuator status includes ready/not ready, start up/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) or variable rates (e.g., event-driven, updating whenever status changes). Most status messages are important messages that need redundancy.

4.7.3.3 Brake Command:

The brake command could be desired brake force or brake pressure. Actuator commands need an update rate faster than 10 Hz, with high priority and message redundancy for safe design.

4.7.3.4 Brake Pressure:

Brake pressure readings from the pressure sensors installed inside pneumatic brake systems can be used for longitudinal control. Brake pressures need an update rate of at least 10 Hz.

4.8 Propulsion Actuator

The function of the propulsion actuator is to deliver the desired driving force through the vehicle engine according to the received command. The light green block on the right side of Figure 4.6 shows the schematics of a general bus engine system.

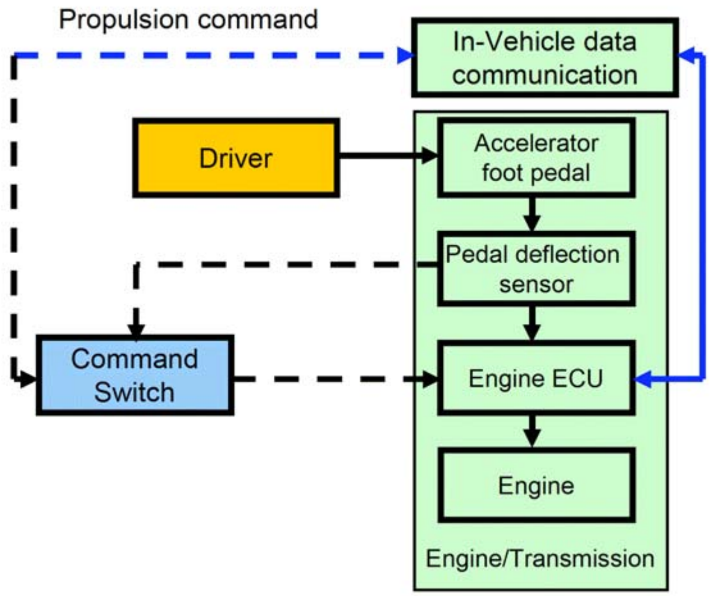


Figure 4.6 Schematic of a General Propulsion Actuator

Since most of today's bus engines are equipped with sophisticated electronic control by the engine ECU, it is really difficult to modify the engine system internally in order to build the propulsion actuator. A possible way to control the engine is through the existing in-vehicle data network (e.g., J1939 serial bus). Although engine commands are defined in the SAE J1939 standard, some engines do not support these commands right now (e.g., the CNG engine used in the New Flyer 40' CNG bus described in Section 2.6.1). If the engine is not configured to support the J1939 engine command, as described in Section 2.6, most of today's buses are equipped with an electric accelerator pedal consisting of an idle switch and pedal deflected angle sensor. The measured pedal deflected angle will be used as an acceleration command for the vehicle engine. So another method for propulsion actuation is to replace the pedal deflection angle sensed by the sensor with a command issued by the longitudinal controller. This requires a command switching mechanism or circuit so that the insertion of the propulsion command will not interfere with the driver's manual operation. This means whenever the driver presses the accelerator pedal, the actuator should switch to the manual operation mode.

4.8.1 Mechanical Installation and Electrical Power Supply

The design should not interfere with the manual operation of the bus driver. The vehicle shall be able to provide enough electrical power to the propulsion actuator

4.8.2 Data Communication

The messages from and to propulsion actuator block are listed as follows:

4.8.2.1 Actuator ID:

Actuator ID gives a unique identification of the messages sent to/from propulsion actuator, especially when multiple redundant actuators are employed.

4.8.2.2 Propulsion Command:

A propulsion command can be a request for engine speed/torque or an equivalent pedal voltage. The command needs an update rate of at least 10 Hz, with high priority and message redundancy for safety.

4.8.2.3 Actuator Status:

The actuator status includes ready/not ready, start up/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) or variable rate (e.g., event-driven, updating whenever status changes). Most status messages are important messages that need redundancy.

4.9 Conclusions and Findings

This chapter has addressed the vehicle interface requirements, and in particular how the important VAA system functional blocks can be designed to accommodate different VAA technologies and different existing vehicle subsystems. A modular VAA system architecture is established first, and then the interface related VAA system functional blocks are identified. The interface requirements are defined for each VAA system functional block in three major categories: mechanical installation, power supply and data communication. Special attention is paid to the data communication requirement.

5.0 Vehicle Testing and Results

5.1 Objectives

As mentioned in the previous chapter, the interface requirements can be grouped into three major categories: mechanical installation, power supply and data communication. The focus of mechanical installation requirements is to satisfy the geometric space constraints imposed by existing bus designs. Such requirements are straightforward and very specific to particular bus designs. The "heavy-duty" nature of transit buses usually can provide enough electrical, pneumatic and hydraulic power for the VAA systems. The only remaining problem is to transform this power into an appropriate form that can be utilized by the VAA system. For example, 12 and 24 volt are the most popular DC power supplied by buses' electrical power systems (Section 2.5). The electronic components of the VAA system may want different voltage levels, so different DC-DC converters may be needed to convert the DC power supply to the desired level. Again, the choice of voltage level really depends on the selection of specific VAA system electronic components, and may vary from design to design. Compared with mechanical installation and power supply, the requirements for data communication are less straightforward and more general across different vehicle platforms and different VAA technologies. The effects of some important data communication characteristics such as network transmission speed and message encoding length on the performance of VAA application are not completely clear *a priori*, and therefore need to be determined through testing.

The vehicle testing at the PATH Richmond Field Station test track served several purposes:

- Vehicle testing is necessary to determine the effects of some important data communication characteristics such as network transmission speed and message encoding length on the performance of key VAA applications.
- The original centralized system architecture on the advanced BRT vehicles previously developed by PATH was changed to a simplified version of the modular system architecture proposed in this report. The comparison of these two different system architectures also illustrates the advantages of the modular system architecture.
- The development of the field testing system provides an example of how to implement the proposed interface requirements.
- As mentioned in Section 4.3, the development of data communication requirements is focused on the application layer, where it can be implemented on top of different network communication technologies. Therefore, the development of the vehicle testing system provides a feasibility study of the implementation of the proposed data communication based on the popular SAE J1939 protocol.

5.2 Experimental Protocols

Since the PATH Richmond Field Station test track was the only test track that was available for use and only low-speed testing can be performed there, VAA-PD was chosen as the application for testing. Although VAA-PD is limited to low vehicle speeds, its implementation involves both longitudinal control and lateral control. Most of the interface related VAA subsystems (e.g. vehicle positioning, vehicle state sensing, steering actuator, propulsion actuator and brake actuator) and existing vehicle subsystems (e.g. power steering, engine/transmission, pneumatic brake system and in-vehicle network communication) are involved. Therefore interface requirements can be fully tested using the VAA-PD application.

Figure 5.1 shows the final docking section of the test track. At the beginning of the docking curve, the bus is driven manually. The transition to the automatic control mode is initiated after magnets in the track are recognized by the VAA-PD sensing system. The transition can be initiated by the driver or by "automated transitioning". The automatic control mode can be lateral (steering) control only or both lateral control and longitudinal control, depending on the driver's selection. After the transition to the automatic mode, the bus steers itself along the predetermined magnetic track. If the automatic longitudinal mode is selected, the bus accelerates and decelerates to about 10 mph and cruises at this speed. Before stopping at the bus station, the bus makes a full lane change following the magnetic track. If the automatic longitudinal mode is activated, the bus stops automatically at the docking station. Otherwise, the driver needs to control the speed of the bus to stop at the docking station.

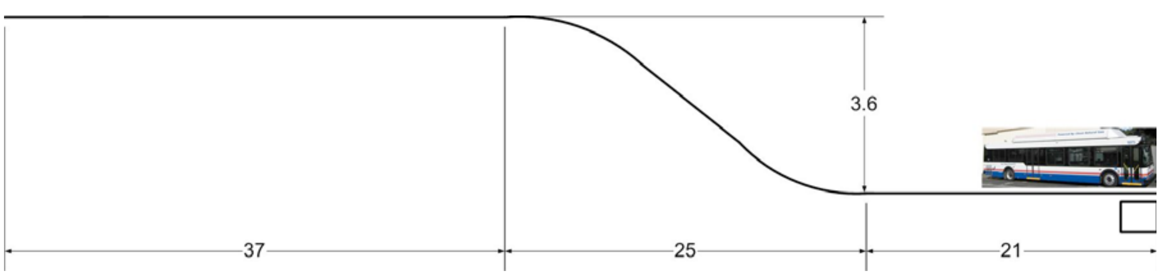


Figure 5.1 Final docking part of PATH Richmond Field Station test track (dimensions in meters, not shown to scale)

The vehicle testing was conducted as follows: The bus was modified according to the interface requirements described in this report. Since data communication was the focus of the vehicle testing, a simplified modular system architecture was adopted to save development time. Although it is simplified compared with the architecture proposed in Section 4.1, the data communication aspects were well preserved. The bus was first operated on the test track to study the basic feasibility of the interfaces. Then some of data communication characteristics such as network transmission speed and data encoding length were modified to study their effects on the performance of the VAA-PD system.

5.3 Test Vehicle Configuration

The test vehicle is a modification of the advanced BRT vehicle previously developed by PATH. The original centralized system architecture was modified to a simplified version of the modular system architecture. The system software architecture was also modified to accommodate the change of system architecture. The data communication among the different functional blocks of the VAA-PD system was implemented in the popular SAE J1939 protocol. The original configuration of the vehicle is described in Section 5.3.1, followed by descriptions of the modifications that were made for this project.

5.3.1 Test bus hardware configuration

A New Flyer 40' CNG bus was equipped for the precision docking maneuver as shown in Figure 5.2. Magnetometer sensors were installed under the bus to detect magnets buried in the road at a longitudinal separation of one meter. The magnets provide both lateral and longitudinal position reference information. The throttle actuator on this bus was designed to emulate the pedal deflection voltage of an electronic accelerator pedal (Section 2.4). The original pneumatic brake system was modified to be actuated by the computer. "Off-the-Shelf" products, Proportion-Air's QB1 proportional pneumatic valve and Proportional-Air R series volume booster, were used for the brake actuator. Pressure sensors were installed to measure the internal pressures of the brake actuator and the pneumatic brake system. The internal vehicle data network (J1939 bus) of the CNG bus was tapped to receive information on the engine and transmission states, such as vehicle speed, engine speed and gear position, which are broadcast by the engine and transmission Electrical Control Units (ECU). The vehicle control and signal processing program ran on a single on-board PC104 computer under the QNX real-time operating system in the original VAA bus configuration.

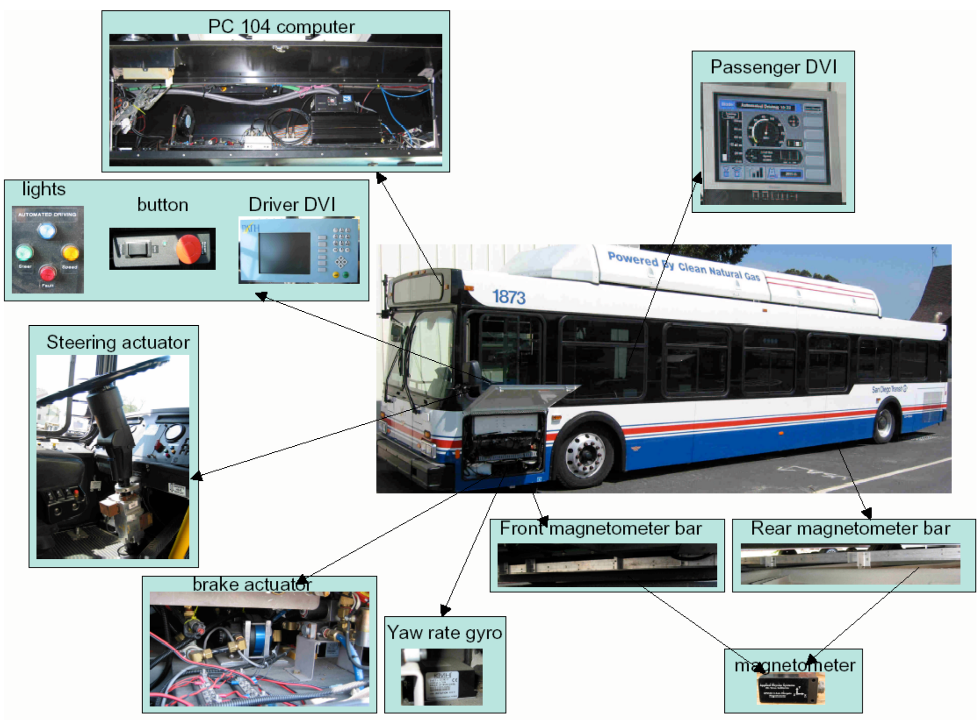


Figure 5.2 Test bus hardware configuration

5.3.2 Testing System Architecture

As shown in Figure 5.3, the original PATH VAA system adopted a centralized system architecture. All the sensors and actuators were directly connected to a central computer, which hosted the processes such as magnetic sensing processing, steering servo, vehicle state sensing and controller. Due to its graphics-intensive application, the DVI function was hosted in a separate DVI computer. The DVI computer communicated with the central computer through a serial port. The drawbacks of such a system architecture are obvious. First, all the real-time processes such as controller, steering servo and magnet sensing processing resided in the same computer, where they were competing for the limited CPU power. To satisfy the real-time constraint, the sampling rate of each program had to be chosen carefully. Second, all the wires to/from sensors/actuators had to be routed to the central computer, which not only complicated the wire routing but also introduced possible electro-magnetic noise. For example, the centerpieces of the magnetic guidance system are two magnetometer bars, each of which includes seven magnetometers. Each magnetometer has three outputs, representing the magnetic field strength in three orthogonal directions. That alone introduced 42 wires routed to the central computer, without counting the ground and power. Finally, in such a centralized architecture, the reliability of the central computer is critical.

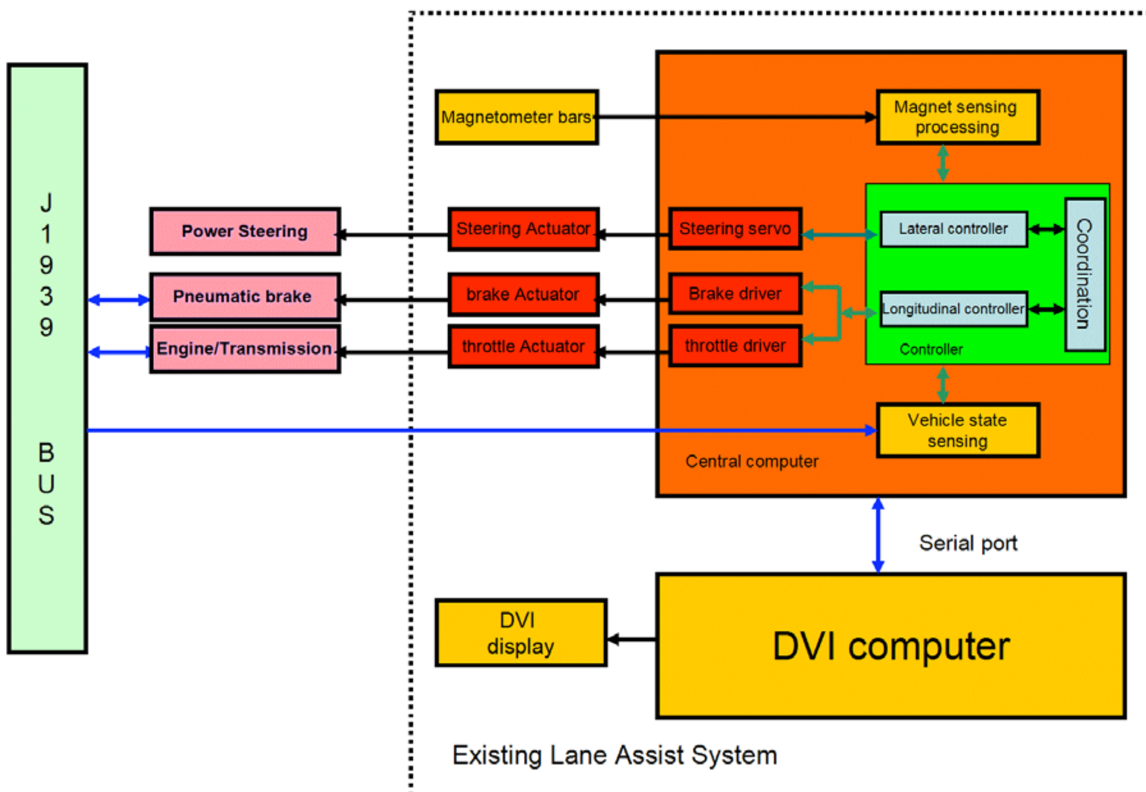


Figure 5.3 Original PATH VAA System Architecture

Although a fully distributed modular system architecture is suggested in Figure 4.2, a more simplified version was adopted for the field testing due to the emphasis on the data communication. The functions of the central computer in Figure 5.3 are separated into two computers: control computer and sensor/actuator computer. The sensor/actuator computer, together with sensors and actuators, forms a big block of “smart” sensors and actuators instead of the individual “smart” sensors and actuators proposed in the fully distributed system architecture version. The sensor/actuator computer is connected to the control computer through a dedicated CAN bus, called the VAA data bus. Such a simplified version may not take full advantage of the proposed distributed system architecture (e.g. all the wires to/from sensor/actuator still have to be routed to the sensor/actuator computer in the simplified version), but it does relieve the computational burden of the original centralized system architecture and introduces the same data communication as the proposed fully distributed system architecture, which is the main focus of the vehicle testing.

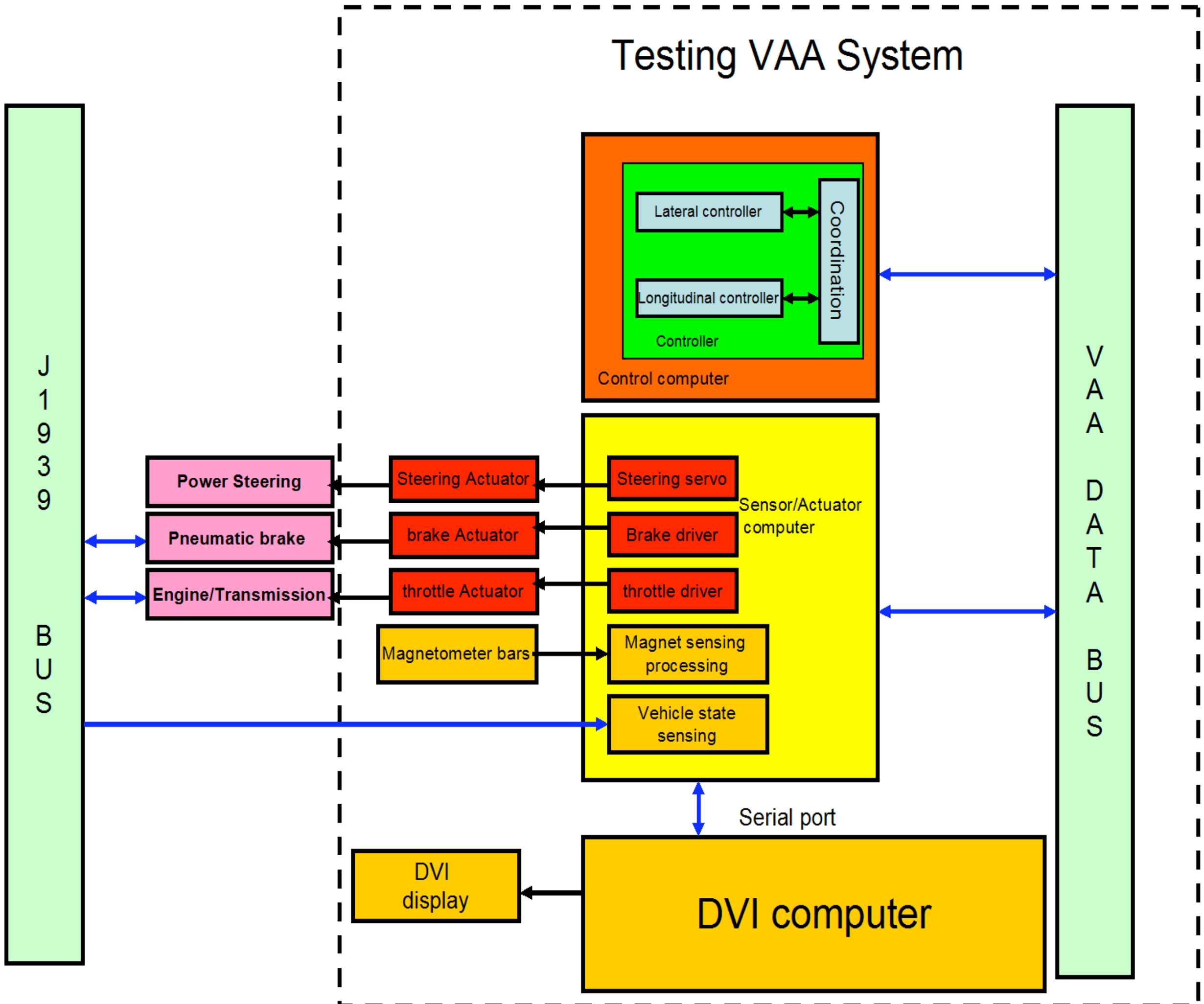


Figure 5.4 Interface Requirement Testing System Architecture

5.3.3 Testing System Software Architecture

Figure 5.5 shows the software architecture of the sensor/actuator computer. The important processes and their functions are:

- veh_bus: the vehicle I/O process, which deals directly with hardware drivers such as serial ports, counter, A/D and D/A card.
- steerctl and t_driver: the processes dedicated to the steering actuator, including position servo, fault diagnostic and actuator mode switching.

- Magnet signal processing: magnetometers' readings are processed and vehicle lateral position is calculated in this process.
- CAN bus input/output: the processes dedicated to the data communication with the control computer.
- rdj1939: the process reading from the existing vehicle J1939 bus.

All the processes communicate with each other through a database (shared memory managed by db_slv).

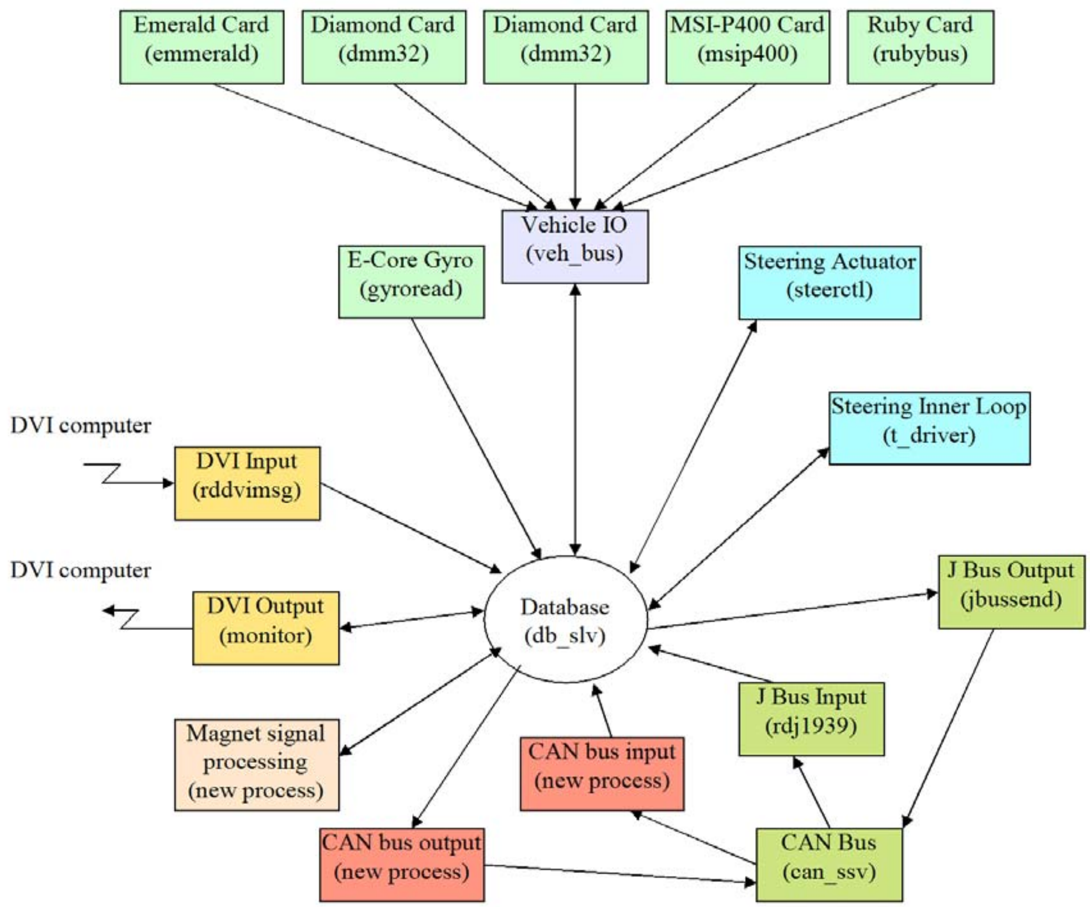


Figure 5.5 Software Architecture of Sensor/Actuator Computer

Figure 5.6 shows the software architecture of the control computer. The important processes and their functions are:

- bus_long: the process responsible for vehicle longitudinal control
- bus_lat: the process responsible for vehicle lateral control and coordination
- CAN bus input/output: the processes dedicated to the data communication with the sensor/actuator computer

Similar to the sensor/actuator computer, all the processes communicate with each other through a database (shared memory managed by db_slv).

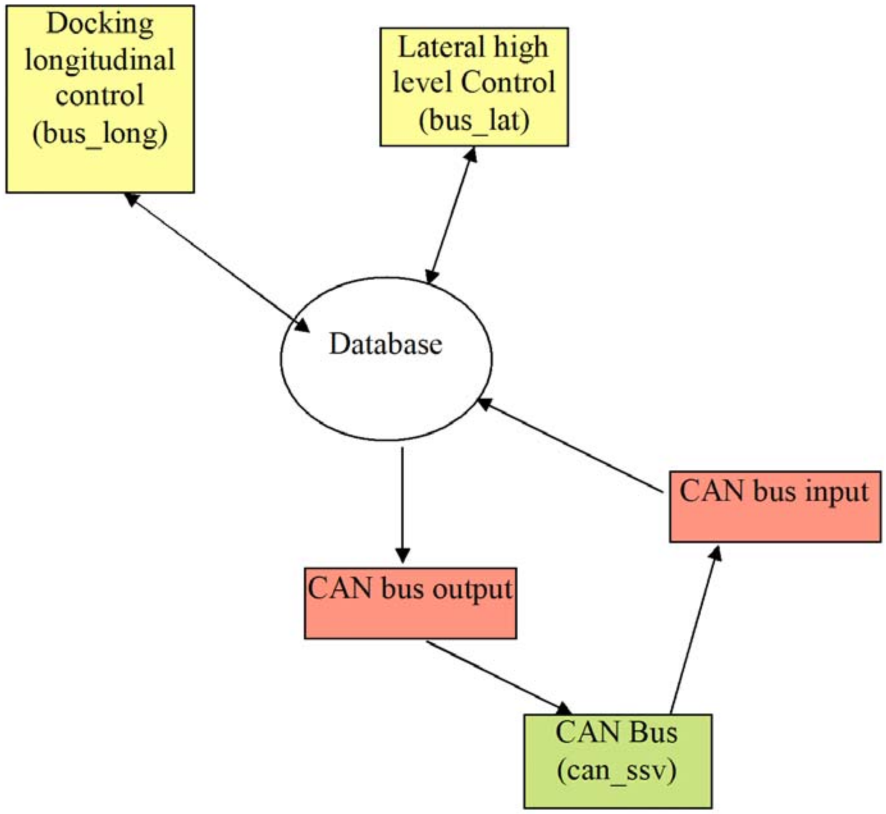


Figure 5.6 Software Architecture of the Control Computer

5.3.4 Data Communications

The SAE J1939 standard is a higher-level protocol designed for use in heavy-duty vehicles with a Controller Area Network (CAN). A standard message set has been defined for the communications among ECUs of transmission/engine, ABS and other components. For the future functional expansion and special manufacturer's proprietary functions, undefined message set space is reserved. The implementation of data communication between the control computer and sensor/actuator computer utilizes the reserved undefined message set space. Table 8.1 and Table 8.2 in Appendix F summarize the definition and timing of messages exchanged between the control computer and sensor/actuator computer. Parameter group number (PGN) is the unique reference number for each J1939 message. Message name (MSG name) specifies each message's name and its origin and destination. Several fields are assembled into one message. BYTES specifies the byte address of each field in the message. Range provides the possible range of each field, while scaling is used to achieve the desired resolution. The update interval of each message is also listed in the table.

5.4 Network Transmission Speed and its Effects

The SAE J1939 protocol is a vehicle application layer built on top of the CAN bus. Since the CAN bus uses an event-driven communication protocol, there is no guarantee of timely message delivery. When the network transmission speed is slowed down and the network bandwidth becomes the bottleneck, message collisions and delays are inevitable. Excessive delay of message delivery will degrade the performance of the VAA-PD system and could even destabilize it, so it is necessary to study the network transmission speed and its effects on the VAA system. In the following study, the CAN bus load is calculated at different network transmission speeds. Then the relationship between bus load and message delivery timing is shown experimentally. Finally, the effects of network transmission speed and CAN bus load on the VAA-PD system performance are presented.

5.4.1 CAN Bus Load Calculation

The SAE J1939 protocol uses an extended CAN bus message, which has a 29 bit CAN identifier. An extended CAN bus message data frame is composed of several fields as shown in Figure 5.7 The length of each field is listed in Table 5.1.

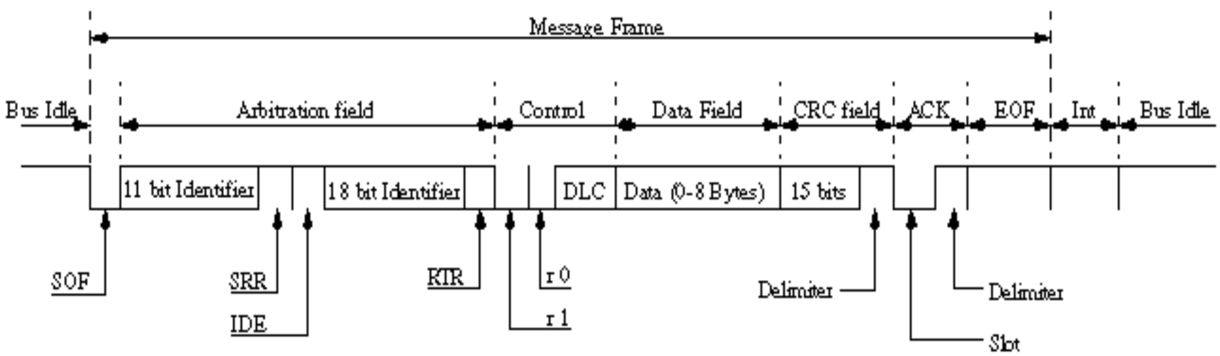


Figure 5.7 Extended CAN Bus Message Data Frame

Table 5.1 Extended CAN message data frame length

	Field length (bit)	Subject to bit-stuffing
Start of Frame (SOF)	1	Yes
Arbitration Field (including SRR, IDE and RTR)	11+2+18+1	Yes
Control (r1, r0 and DLC)	6	Yes
Data	64	Yes
CRC	15	Yes
CRC Delimiter	1	Yes
ACK	2	
EOF/IFS	10	

The actual length of each CAN message is data dependent. The CAN protocol uses bit-stuffing to facilitate bit synchronization by the receiver nodes. The bit-stuffing rule is that a sequence of more than five equal bits has to be broken by insertion of a stuff bit. The maximal length of an extended CAN message data frame is $s = \frac{119}{5} + 131 = 155$. The utilization of the bus is defined as

$$U = \sum_i \frac{C_i}{T_i}$$

where i is the number of periodic transmissions on the bus, C_i is the transfer time for this message and T_i is the period for sending of message i. The utilization is a measure of how much load there is on the databus.

Figure 5.8 shows the databus load for the experimental system when CAN bus transmission speed was chosen as 50 kbit/sec, 125 kbit/sec, 250 kbit/sec, 500 kbit/sec and 800 kbit/sec. The utilization under 0.5 usually indicates that the databus load is low, but if the utilization is above 1.0, the databus is overloaded.

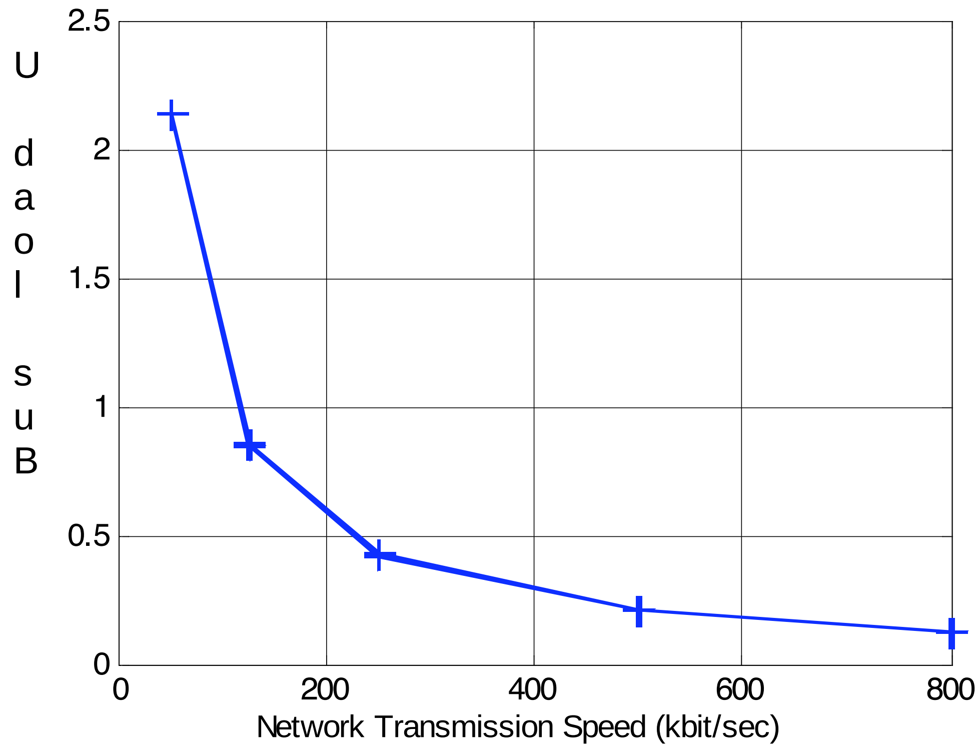


Figure 5.8 Network Transmission Speed and Databus Load

5.4.2 CAN Bus Message Timing

For the study of CAN bus message timing of the field testing system, the CAN bus network transmission speed was set at 50 kbit/sec, 125 kbit/sec, 250 kbit/sec, 500 kbit/sec and 800 kbit/sec. A time stamp was recorded when a message was received. For each message, two reception time stamps were compared to get the time interval of message reception. The following figures show the reception time intervals of each message for the sensor/actuator computer.

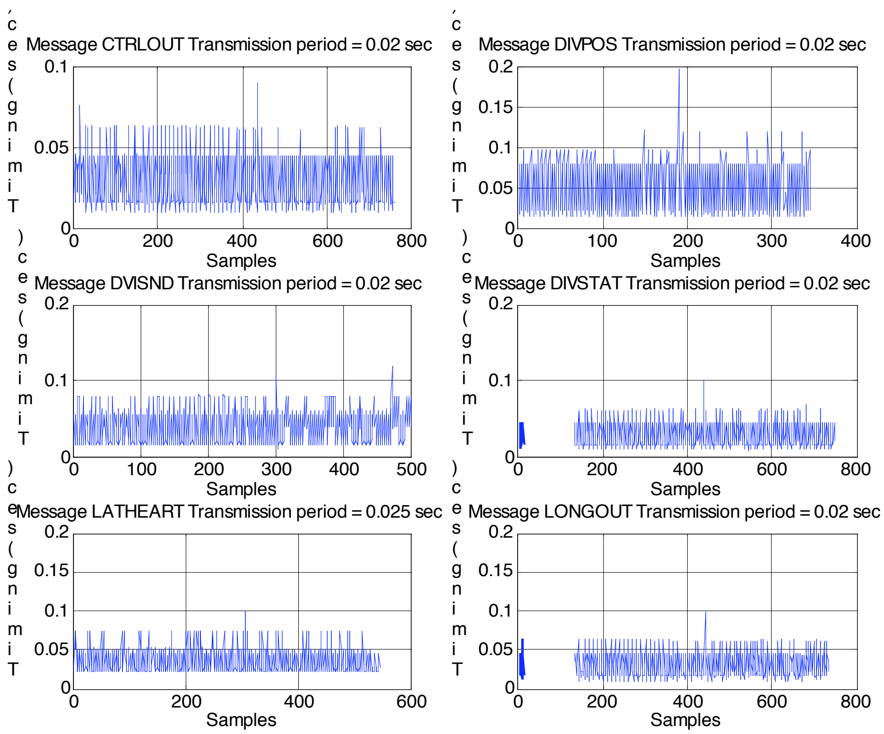


Figure 5.9 Message Timing for 50 kbit/sec

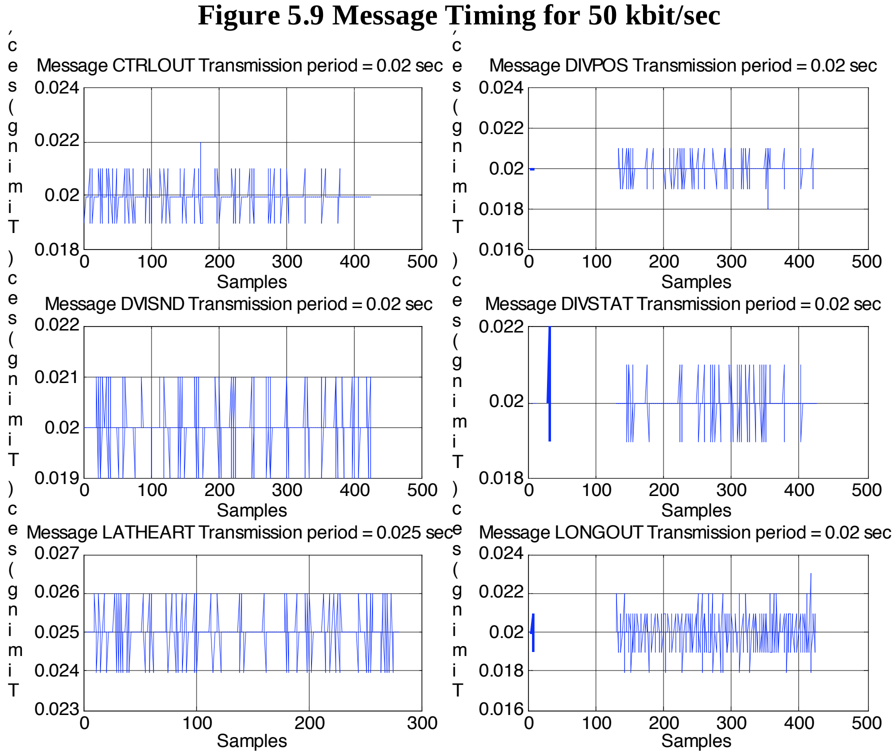


Figure 5.10 Message Timing for 125 kbit/sec

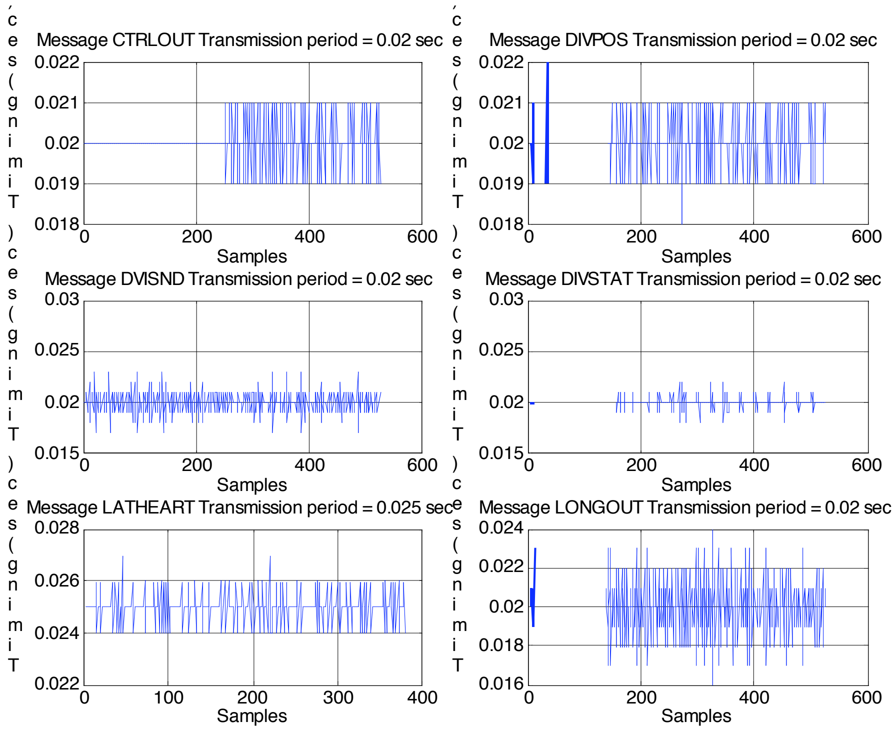


Figure 5.11 Message Timing for 250 kbit/sec

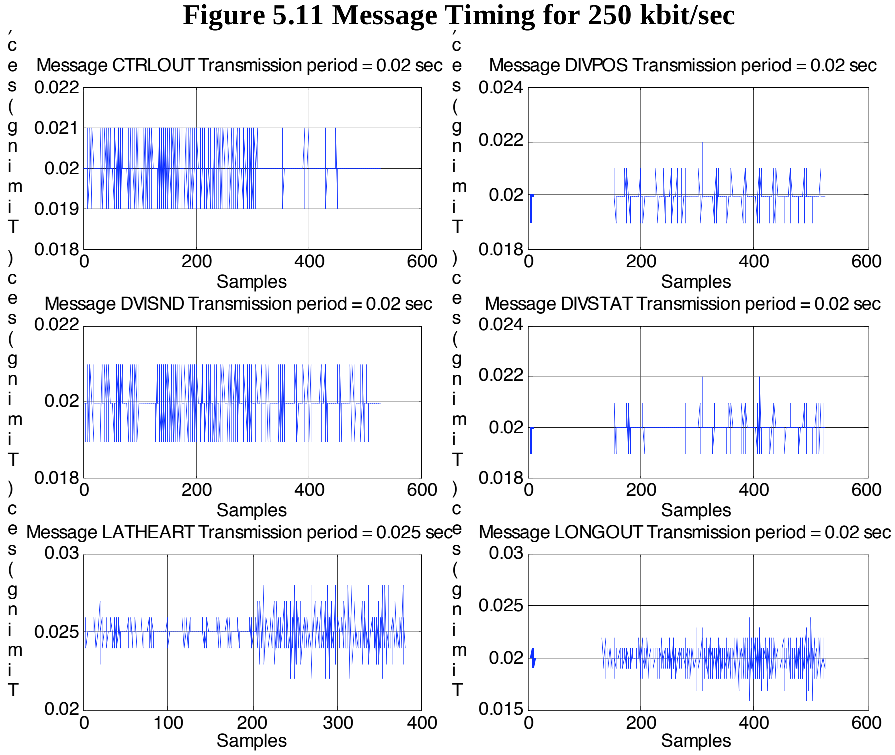


Figure 5.12 Message Timing for 500 kbit/sec

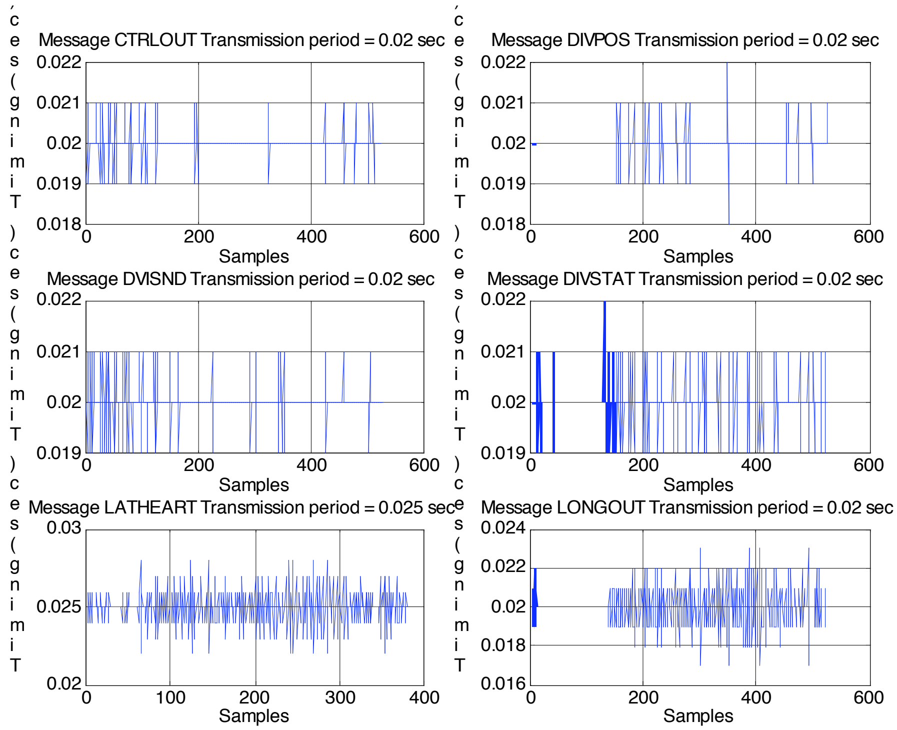


Figure 5.133 Message Timing for 800 kbit/sec

When the network transmission speed was 50 kbit/sec, the databus load was over 2 as shown in Figure 5.8, and it showed significant time delay in Figure 5.9 for the message timing. When the databus load dropped under 1 for the network transmission speed higher than 50 kbit/sec, the message timing also improved significantly. However, it did not show much improvement when the speed increased above 125 kbit/sec (Figure 5.10 Message Timing for 125 kbit/sec

-Figure 5.13). Therefore the databus load should be designed to be smaller than 1, although a 0.5 databus load will be desirable since the network transmission speed for the CAN bus can be as high as 1 Mbit/sec.

5.4.3 Precision Docking System Performance

Precision docking experiments were conducted at the Richmond Field Station on the S-curve docking track shown in Figure 6.1, where the bus has to make a full lane change before completing the precision docking. Figure 5.14 shows the docking performance for several network transmission speeds. There is no plot for 50 kbit/sec because the system was unstable at such a slow network transmission speed due to message delivery delays. For the purpose of comparison, the docking performance of the original system with the centralized system architecture is also plotted in the figure. The large tracking errors before the final docking were due to the sharp turn during the full lane change, but the final docking errors are kept well below 5 cm. The docking performance in Figure 5.14 is quite similar for the different network transmission speeds and original system. However, high frequency chattering of the steering wheel was observed for network transmission speeds slower than 500 kbit/sec during experimentation. Such steering wheel chattering is the combined effect of steering wheel freeplay (about 20 degrees in the steering wheel angle for the PATH test bus) and message delivery delay. It does not mean that a 500 kbit/sec speed should be specified for every system, but only that it was needed here because of the steering wheel freeplay on this vehicle.

In such a distributed system architecture, data communication is an integral part of the VAA system, which is a real-time control system. Its requirements, such as network transmission speed, have to be specified so that the system-level performance requirements can be achieved. For example, a smaller steering wheel freeplay would mean that a larger message delivery delay could be tolerated, and hence a slower network transmission speed could be chosen.

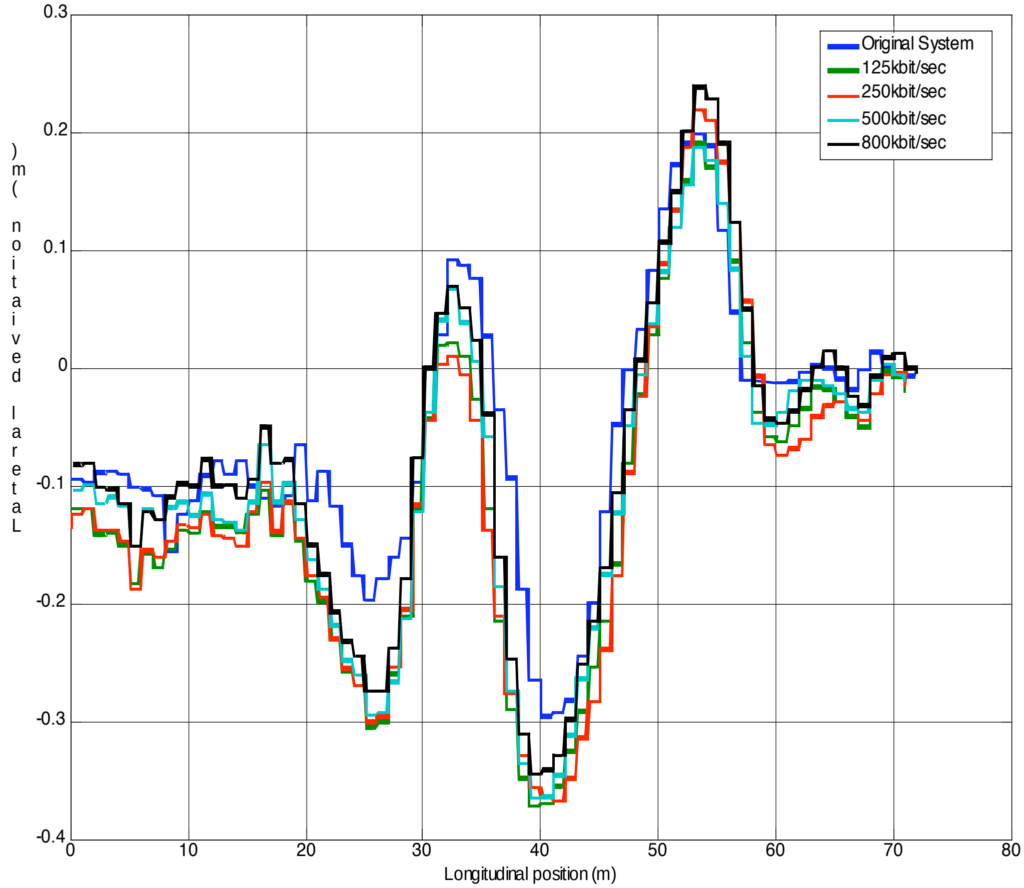


Figure 5.14 Docking Performance for Different Network Transmission Speeds

5.5 Message Length

To ensure that the data exchanged among the functional blocks through the data communication bus has enough precision within its possible range, yet does not use any more of the communication bandwidth than necessary, numerical encoding schemes such as fixed point limited range or integer case encoding of finite possibilities can be used. Experiments were conducted for different encoding lengths on the steering angle. For the 4 bytes (32 bits) representation, resolution under 1 degree in the steering wheel angle was achieved. For the 9 bit representation, the resolution was only around 3 degrees in the steering wheel angle. Figure 5. shows the docking performance for the different encoding lengths. The performance was similar before final docking, but due to the lower resolution of steering angle, the 9 bit representation showed a larger final docking error. Although the final docking error was still kept within 5 cm for both cases, the steering wheel showed severe chattering movement during precision docking using the 9 bit representation. Therefore the experimental results show that message coding length should be chosen such that the desired sensor/command resolution can be achieved. In this case, the steering angle resolution was specified to be no more than 1 degree in steering wheel angle in the previous section. The 9 bit representation can only achieve 5 degrees resolution in the whole sensor range, which will result in poor system performance.

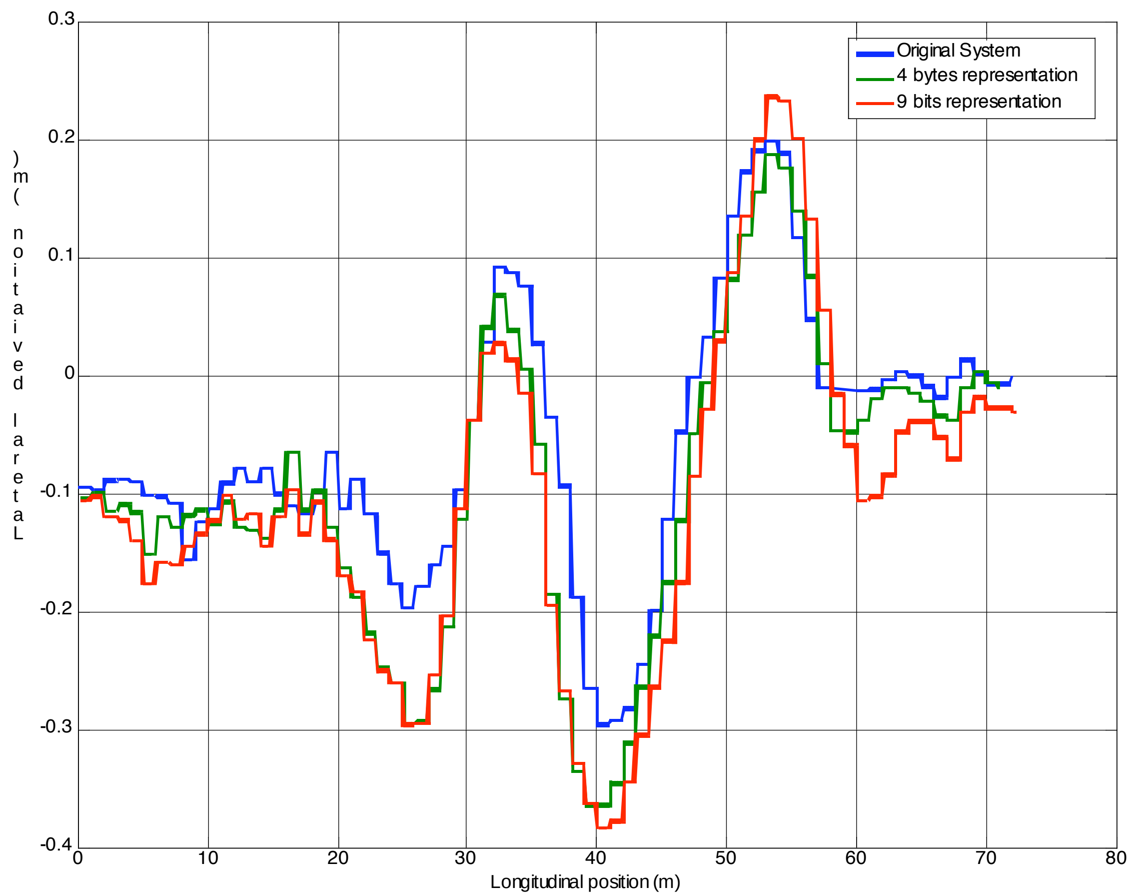


Figure 5.15 Docking Performance with Different Message Encoding Lengths

5.6 Conclusion and Findings

5.6.1 Key Observations

Following is a summary of key observations from vehicle testing:

- Following the interface requirements developed in the previous chapters, the test bus was capable of performing precision docking within the desired performance requirements
- The proprietary message section of SAE J1939 standard can be used for the data communication for VAA systems.
- The data communication for VAA systems can be implemented on top of the popular CAN protocol.
- Some of the network characteristics such as network transmission speed and message encoding length could affect the system performance if they are not chosen properly, and they need to be chosen based on the specific technical characteristics of the host vehicle.

5.6.2 Analysis of the findings in regard to the requirements

The results of the vehicle testing have led to the following conclusions regarding the interface requirements for VAA systems:

- The modifications of the experimental bus showed that the proposed interface requirements can be implemented on a transit bus. The successful completion of precision docking maneuvers by the bus clearly demonstrated that the proposed interface requirements can support VAA applications.
- Using the proprietary section of the SAE J1939 standard is a convenient way to implement data communication for the VAA system and is compatible with current common industry practice.
- Although the CAN protocol is an event-triggered communication protocol, it can be used for a real-time control system like VAA-PD with stringent timing requirements when the parameters (e.g. network transmission speed and data encoding length) of the network are chosen properly.
- Network transmission speed is a critical parameter for the data communication design. Network load (section 5.4.1) is a good indicator for the selection of network transmission speed. As shown in experimentation, a network load smaller than 0.5 is preferred for the CAN bus implementation.
- Data encoding length is another design parameter for the data communication, to ensure the precision of transmitted data. For example, the steering angle is an important measurement for the lateral control function of the VAA-PD and VAA-VG applications. To achieve less than 1 degree (in steering wheel angle) precision across the full steering wheel operation range, at least an 11 bit representation should be used for transmission of the steering angle message.

6.0 Conclusions

Vehicle Assist and Automation technologies have been under development in recent decades and are starting to become available for transit applications. The transit industry recognizes that BRT buses will primarily be built upon existing bus products. In order to accommodate a variety of VAA system technologies and suppliers and the diversity of existing transit vehicle subsystems, it is necessary to develop standard interfaces between new VAA subsystems and the related existing vehicle subsystems. This report discusses the interface requirement issues, proposes two sets of interface requirements and presents perspectives on the next steps toward the implementation and commercialization of VAA technologies. The report recommends two sets of requirements, including in-vehicle interface requirements for VAA systems and requirements for the vehicle-to-roadway infrastructure interfaces.

6.1 Proposed Infrastructure Interface Requirements

The running way, station platform and infrastructure-based reference system are integral parts of the VAA system and therefore need to be compatible with the VAA vehicles. Interface requirements between the infrastructure and BRT vehicles need to be defined to support the design of new infrastructure or modifications of existing infrastructure. Based on these needs, the following interface requirements are defined:

- Running way: Narrow lane design is one of the major VAA-VG system benefits. Section 3.2 discusses the lane width requirements and recommended how to define the minimum desirable width of running way in straight sections. Since the required lane width increases on curves as the radius of curvature decreases, Section 8.3 provides the recommended curve offset for standard simple curves. Other factors, such as pavement designs, that will impact ride quality are also discussed.

- Stations: The implementation of VAA-PD precision docking imposes some constraints on station platform design. Section 3.3 discusses these constraints and defines factors that need to be considered in the design of the boarding platform height, orientation and the geometry of the entrance from and exit to the running way.

- Vehicle exterior geometry: Because the vehicles need to be maneuvered closer to the station platform under VAA-PD than under manual driving, existing exterior design features such as raised rubber fenders, combined with indented door steps, increase the docking gap. Section 3.4 discusses the design issues associated with bus exterior geometry and recommends possible ways to modify traditional bus body design (e.g., by extending the floor out to the edge of the fenders) in order to facilitate the implementation of VAA-PD.

- Infrastructure-based lane tracking references: Infrastructure-based references are integral parts of the vehicle and lane position sensing for VAA-PD and VAA-VG. The requirements of the reference system are closely coupled with the system performance requirements. Additionally, because different guidance technologies use different reference systems (e.g., lane stripes for vision-based guidance system, satellite and digital map reference for GPS-based guidance system and permanent magnets for magnetic guidance system), the requirements differ significantly. Section 3.5 discusses infrastructure-based reference requirements for three typical guidance technologies, including magnetic reference system, GPS-based reference system and vision-based reference system.

6.2 Proposed Vehicle Interface Requirements

The study of interface requirements has followed a systems approach to investigate needs, technical issues and challenges for VAA technologies to interface with existing buses. It also takes into consideration the existing bus designs and the VAA system designs and requirements in order to allow the VAA interface requirements to be consistent and compatible with the potential VAA system designs and to support VAA system requirements for performance, reliability, safety and maintainability. The interfaces between the VAA systems and existing bus components are classified in three major groups: mechanical installation, power supply and data communications. As an important step toward development of the VAA interface requirements, this study developed a modular distributed VAA system architecture which clearly defines the interfaces and communications among the VAA subsystems and their interfaces with the other vehicle components. This architecture also uses existing industry standards and practices, such as a dedicated in-vehicle data bus. Within the framework of the modular system architecture for VAA, interface requirements have been defined for the primary VAA subsystems, including vehicle positioning, vehicle state sensing, steering actuator, propulsion actuator and brake actuator. Detailed analysis has been conducted on the data communication among VAA subsystems and between the VAA subsystems and the principal components of the transit bus. The interface requirements for each VAA subsystem are summarized as follows:

- Vehicle and lane position sensing: Bus-borne vehicle and lane position sensing is a relatively independent VAA system functional block Because vehicle and lane position sensing can be implemented using different technologies, e.g., vision, magnetic and GPS based sensing, the mechanical installation requirements will be determined by the specific adopted technology. The level of electric power supply needed will also depend on the specific electronic components selected.to implement the system. However, regardless of the technologies applied, the characteristics of the sensor outputs need to meet a common set of performance requirements and the data communication interfaces with other VAA subsystems need to be technology independent. Section 4.4 discusses the performance needs for vehicle and lane position sensing and focuses on the definition of the data communication interface between the vehicle and lane position module and other VAA subsystems, specifically the types and frequency of messages needed for vehicle and lane position sensing.
-
- Vehicle state sensing: VAA vehicle state sensing can be achieved through a combination of sensor measurements already acquired for existing vehicle operation purposes, newly installed sensors (when the vehicle state information required by VAA is not currently

available) and data from various VAA components. Section 4.5 discusses the types of sensor information needed for vehicle state sensing and identifies the likely sources of this information. Note that both mechanical and electrical installation of sensors may depend on the type of sensors and their installation methods, so the interface requirements focus on defining the data communication among VAA components and the existing vehicle data network (i.e., J1939) including definition of message types and update frequency requirements.

- Steering actuator: The steering actuator is closely coupled with the existing vehicle steering system and therefore needs special attention. The steering actuator may be an add-on device attached to the existing steering system, an integrated part of a modified steering assist system, or a separate new steering device (e.g., steer-by-wire). Because the VAA interface requirements primarily deal with implementation of VAA capabilities on existing bus designs, we have focused on add-on steering actuators, which would require common interfaces. Note that space is very limited around the steering column, so a compact steering actuator design is required. There are several ways to integrate steering actuation with existing bus steering systems, including implementation of the steering before the power steering box, after the power steering box and inside the power steering box. Section 4.6 discusses the torque requirements for each installation method. Depending on the exact implementation method, sufficient electrical or hydraulic power supply is required. The interface requirements focus on the performance and reliability needs for the steering actuator and the data communication between the steering actuator and other VAA subsystems. In addition to the interface requirements, the freeplay in the existing bus steering system significantly affects the VAA performance.

- Brake actuator: Brake actuation can be implemented through modifications to the existing brake system or using electronically actuated braking system (EBS) technology. However, because EBS is not generally used in the U.S., the interface requirements mainly deal with modifications to the existing pneumatic brake systems. Section 4.7 discusses the installation of the brake actuator and defines the communication between the brake actuator and other VAA subsystems.

- Propulsion actuator: Propulsion actuation is essential for longitudinal control of VAA systems. Since most of today's bus engines are equipped with sophisticated electronic control by an engine ECU, issuing commands through the existing in-vehicle communication network to control the existing engine/transmission system is the desired way to implement propulsion actuation. However, the requirements also address alternative ways of implementing propulsion by modifying the electronic accelerator pedal actuation if the vehicle's engine/transmission system is not configured to react to commands from the in-vehicle communication network. In either case, a common communication interface is needed for the propulsion system. Section 4.8 defines the communication between the propulsion system and other VAA subsystems.

In order to verify the interface requirements defined in this report, testing was conducted using a 40 ft bus instrumented with automated steering and longitudinal control capabilities. The system was set up to emulate the modular architecture, and data communication among the functional components was accomplished by using the messages defined in this requirements document using the existing J-bus and an add-on J-bus. A series of tests was conducted to evaluate the feasibility of the modular system architecture and whether and how the data requirements would affect the system performance. The verification tests validated that the requirements proposed in this document are viable and technically implementable.

6.3 Next Steps

The implementation and commercialization of VAA systems will need to involve bus manufacturers, bus component suppliers, VAA technology suppliers, transit agencies and other government agencies at different levels (federal, state and local). Additional steps need to be taken to advance toward implementation and commercialization of VAA systems:

Because standard interfaces between VAA and existing bus subsystems are critical for larger and cost effective deployments, it is necessary to involve bus manufacturers, bus component suppliers and VAA technology suppliers at an early stage to build consensus on the interface requirements in order to promote:

- Existing or new bus suitability for VAA applications (e.g., bus exterior geometry)
- Minimized variations in design and performance of key bus subsystems (e.g., bus power steering system characteristics)
- Standard interfaces for VAA subsystems, especially for data communications.

Transit operators, particularly BRT interested agencies, are interested in VAA technologies to provide higher operational efficiency and rail-like quality of service. However, because VAA technologies have not yet been widely deployed and transit agencies are conservative about adopting new technologies, it is necessary for FTA and state government agencies to take the lead to support demonstrations of the effectiveness and safety of VAA technologies. Strong commitments from FTA and state government to deployment of VAA systems will also help to convince VAA technology suppliers to invest in the commercialization of VAA systems, thereby jump starting the development process.

7.0 References

[1] New Flyer *Diesel 60' Low Floor Transit Bus Service Manual (SR752)*
[2] New Flyer *CNG 40 ft Low Floor Transit Bus Service Manual (SR722)*
[3] Gillig *Diesel 40 ft Low Floor Transit Bus Service Manual (City of Wilmington)*
[4] http://www.usdoj.gov/crt/ada/reg3a.html
[5] VanHool *A330 Transit Bus Maintenance Manual*
[6] VanHool *AG300 Transit Bus Maintenance Manual*

8.0 Appendices

8.1 Appendix A New Flyer 40' CNG J1939 Message List

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

1. Electronic transmission 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

2. Electronic transmission controller #1

Electronic Transmission Controller #1	Unit	Range	Updating period
shift in process	Status	0/1	10 ms
torque converter lockup engaged	Status	0/1	10 ms
driveline engaged	Status	0/1	10 ms
output shaft speed	RPM	0 to 8031.875	10 ms
percent clutch slip	Percent	0 to 100	10 ms
input shaft speed	RPM	0 to 8031.875	10 ms

3. 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

4. Electronic engine controller #1

Electronic Engine Controller #2	Unit	Range	Updating period
low idle	Status		50 ms
accelerator pedal position	Percent	0 to 100	50 ms
percent load current speed	Percent	0 to 125	50 ms

5. 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

6. 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

7. 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

8. 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	m/sec	-2.170 to +2.170	100 ms

8.2 *Appendix B New Flyer 60' Diesel articulated bus J1939 message list*

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

8.3 *Appendix C Effects of Tight Turning Radii on Needed Lane Width*

Buses equipped with electronic guidance are able to operate in narrower lanes than normal buses. Several existing electronic guidance technologies have been shown to be capable of steering buses in a 10 foot wide lane, which represents a 17 percent reduction from a "normal" 12 foot straight line segment bus lane. On turning segments, physical constraints require a wider lane than straight-line segments, regardless of the accuracy of the steering. The sharper the curve, the wider the lane needs to be (the technical explanation of this is shown below). The following two figures show the additional lane width required as a function of turning radius for a New Flyer 40' CNG and a New Flyer 60' Diesel.

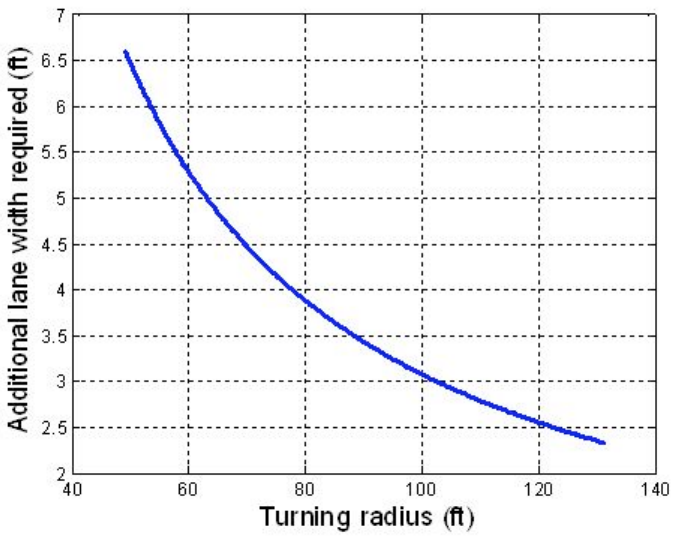


Figure 8.1 Additional Lane Width Required vs Turning Radius for a New Flyer 40' CNG

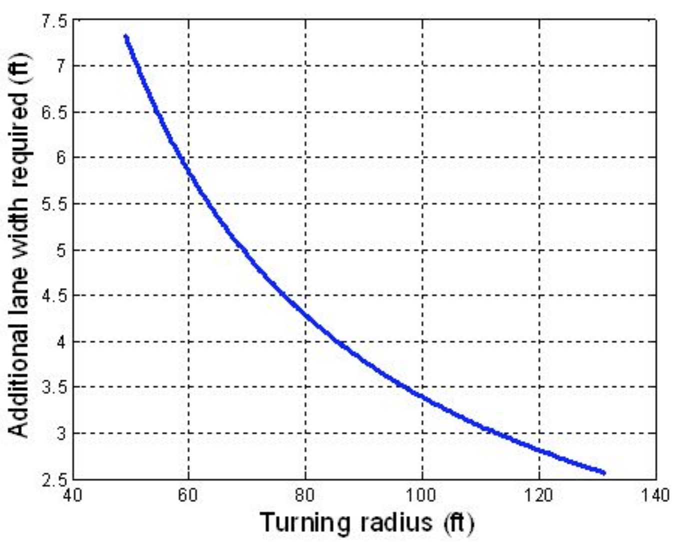


Figure 8.2: Additional Lane Width Required vs Turning Radius for a 60' New Flyer

When the bus is in motion, one of the physical constraints it has to satisfy is a nonholonomic kinematic constraint assuming that there is no sideslip of the vehicle tires. As shown in Figure 8.3, a is the middle point of the bus' rear axle, (x, y) are a's coordinates in a fixed reference frame. θ is the vehicle's orientation angle. The nonholonomic kinematic constraint can be described by

$$\tan\theta = \frac{\dot{y}}{\dot{x}} = \frac{dy}{dx} \tag{C1}$$

where $\dot{x}$ and $\dot{y}$ represent point a's velocity components in the x and y directions.

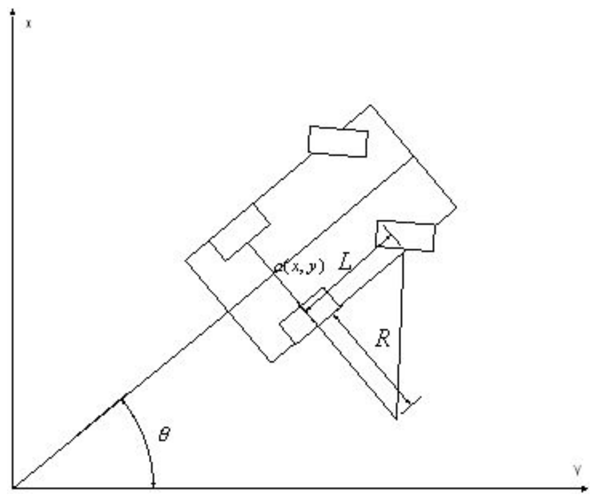


Figure 8.3 Vehicle Motion

One effect of such nonholonomic kinematic constraints is that the rear wheels are always inside the trajectories of the front wheels when the vehicle is turning. To further illustrate this effect, a 40 ft single unit New Flyer bus and a 60 ft articulated New Flyer bus are used as examples.

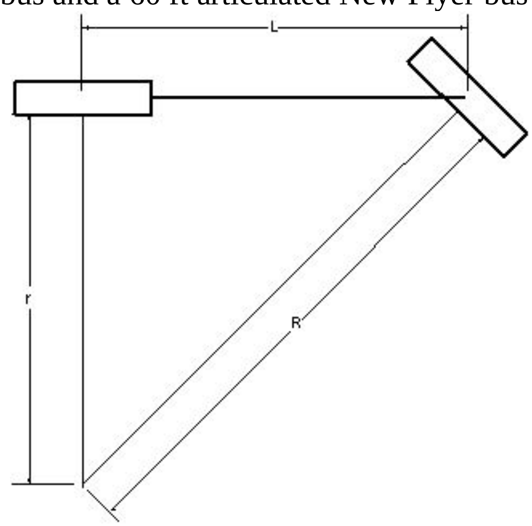


Figure 8.4 Turning Radius for Single Unit Bus

The hypothesis are that there is no sliding on each tire and only geometric relations are considered. As shown in Figure 8.4, the turning radius at the front tire is R, the turning radius at the rear tire is r and L is the wheelbase length. Therefore, the following relationship is known:

$$R^2 = L^2 + r^2 \quad \text{(C2)}$$

From (C2), $R > r$. That means that the rear tire will always have a smaller turning radius compared with the front tire.

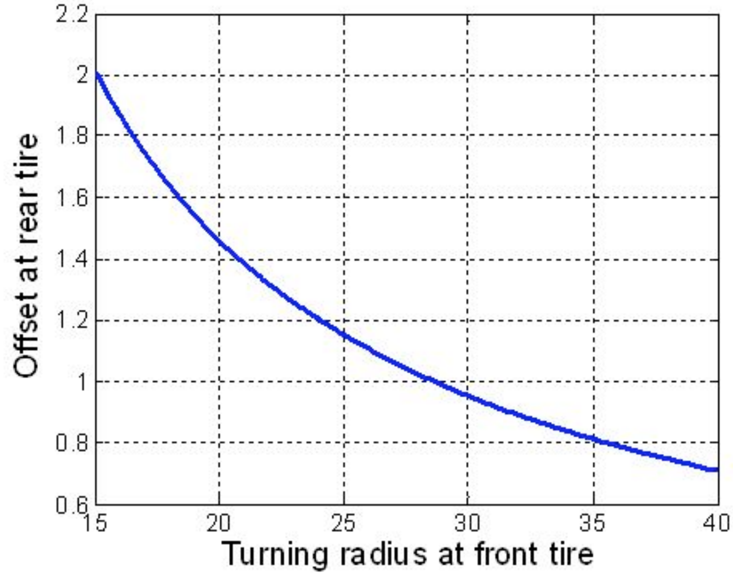


Figure 8.5 Offset at Rear Tire for 40'' Single Unit Bus (m)

Figure 8.5 shows the offset tracking $R - r$ at the rear tire for a New Flyer 40 foot single unit bus.

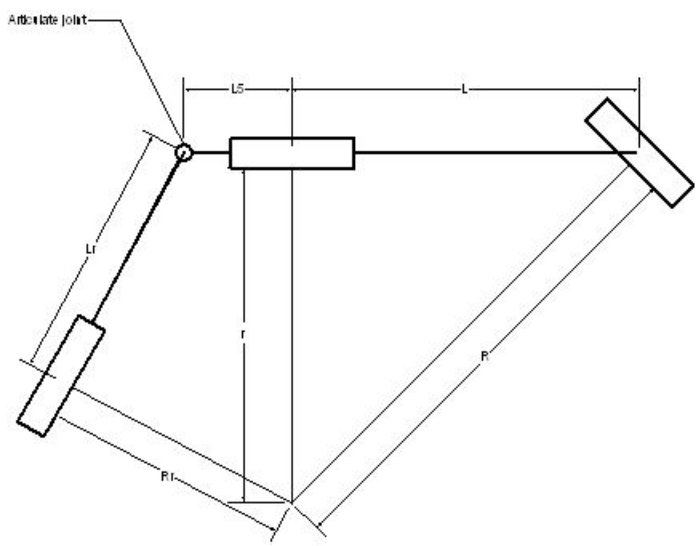


Figure 8.6 Turning Radius of Articulated Bus

As shown in the Figure 8.6, $L5$ represents the distance between rear wheel and articulation joint, Lr represents the distance between articulation joint and rear wheel and Rr represents the turning radius at the rear tire. Given the same assumptions:

$$Rr^2 = R^2 + L5^2 - L^2 - Lr^2 \quad \text{(C3)}$$

Figure 8.7 shows the offset tracking at the rear tire for a New Flyer 60 foot articulated bus.

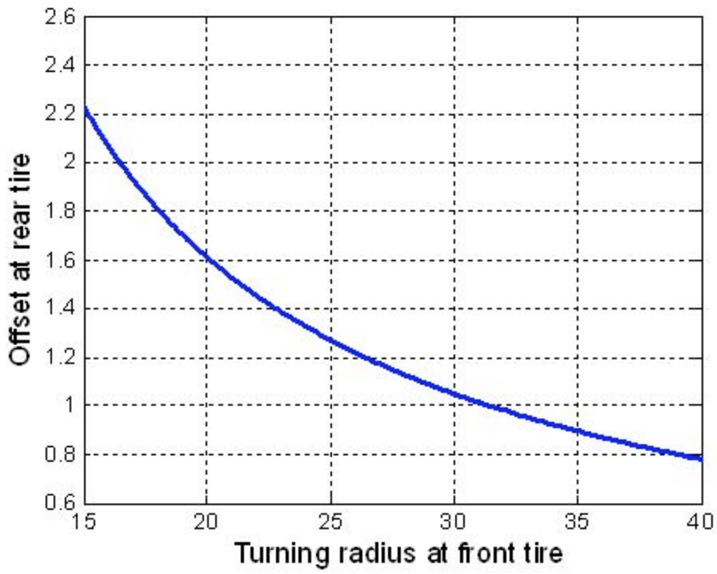


Figure 8.7 Offset at Rear Tire for 60' Articulated Bus (m)

8.4 Appendix D Sensing and actuating requirements

As shown in Figure 4.2, the core of the VAA system is a closed loop control system. Since the vehicle's lateral dynamics and longitudinal dynamics are not generally coupled tightly, such a closed loop control system is usually decoupled into two closed loop control subsystems: a lateral control system and a longitudinal control system. In this appendix, how to determine the actuating and sensing requirement will be illustrated in detail.

- ***Control system sampling rate*** (message update rate): The fundamental vehicle dynamics is usually around 0.5-3 Hz. As a rule of thumb, a sampling rate at least 10 Hz will be enough for the closed loop digital control. This means that the update rate for the critical sensor outputs such as vehicle position, vehicle speed, yaw rate, and brake pressure should be at least 10 Hz. The update rate for the communication messages related to these sensor outputs should also be at least 10 Hz. Similarly, the update rate for the control commands to the corresponding actuators and related messages should also be at least 10 Hz.
- ***Vehicle lateral position sensing***: The required accuracy of the vehicle positioning system is determined by the lane tracking accuracy requirement.
    1. The performance requirement for precision docking is subject to the legal performance requirements from the Americans with Disability Act (ADA). According to the ADA requirements, the horizontal gap between boarding platform and vehicle floor, measured when the vehicle is at rest, shall be no greater than 7.62 cm (3 in). With a minimum allowable gap of 0.5 in., the required gap is 2.5 in., which would give 1.25 in tracking accuracy (+/- 1.25 in.) with a design factor of 1. For a design factor of 2, the tracking accuracy would be 1.25/2 = 0.625 in.(1.59 cm)
    2. The performance requirement for the lane keeping function is determined in a similar fashion based on lane width and vehicle width. For example, under the scenario of 3.2 m (10.5 ft) lane width, 2.59 m (8.5 ft) bus width, 7.65 cm (0.25 ft) minimum clearance, straight road and design factor of 2, the resultant bus tracking accuracy requirement would be 11.4 cm (0.375 ft). Thus the required vehicle lateral positioning sensing accuracy would have to be at least 5.7 cm for lane keeping (to be half of the respective tracking accuracy requirement).
- ***Steering Actuator:*** Since there are many ways to design steering actuators, the requirements will be different for different design methods. Here the add-on electrical motor design is used as an example. Others can be followed in the similar way.
    a. **Local servo loop bandwidth (for the modular system design)**: Since the vehicle fundamental dynamics is around 1 Hz for the modular system design, the local servo loop bandwidth should be at least 4 or 5 Hz for a small amplitude command (e.g. 20 degrees at the hand wheel).
    b. **Local servo loop sampling frequency**: As stated in the local servo loop bandwidth, a minimum 4 or 5 Hz is required, which means that the sampling rate for the local servo loop should be at least 20 Hz, although 40 or 50 Hz is preferred.
    c. **Local servo loop accuracy**: As illustrated in the vehicle positioning accuracy

requirement, the tracking accuracy could be 3.175 cm for precision docking. For a bus with a long wheel base, e.g., 7.5 m for the 40 foot New Flyer CNG bus, the steering angle would need an accuracy of 180/PI *(0.03175/7.5) = 0.16 degree. If the steering box gear ratio is 18, the accuracy at the hand wheel would be 4 degrees. Giving a design factor of 4 to provide room for flexibility in the controller design, the required local servo loop accuracy would then be 1 degree at the hand wheel.

d. **Steering motor power**: The steering motor power is determined by the worst-case scenario. The resistant torque from the steering wheel becomes smaller when the bus is driving at higher speed. The worst-case scenario is when the bus is stopped or moving very slowly, such as at the end of a precision docking maneuver. At the end of precision docking, the bus speed is very slow or almost zero and tire aligning torque is at its maximum. The requirement for the steering motor power is that it must easily overcome this torque. So an experiment similar to the one in Section 2.2.4 is very important to help define the steering motor power requirement.

8.5 *Appendix E Schematics of existing bus sub-systems*

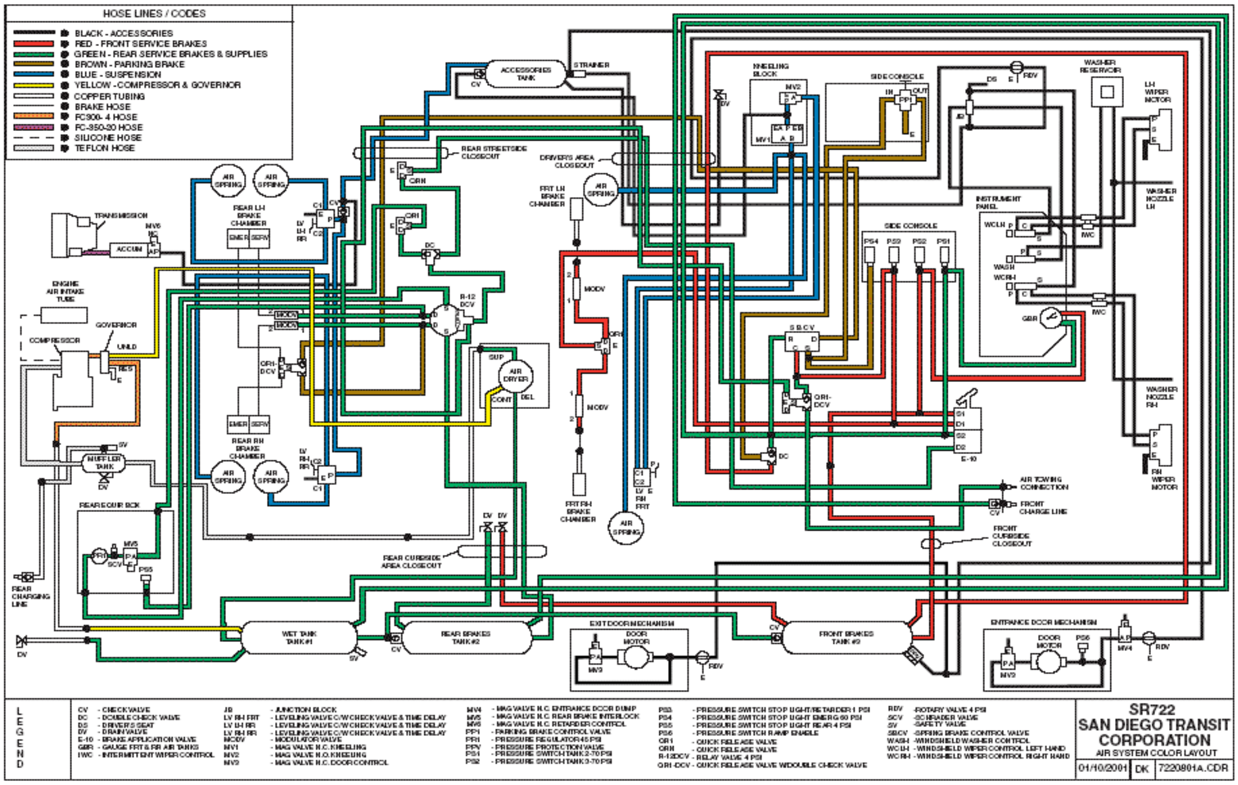


Figure 8.8 Compressed Air System of New Flyer 40' CNG Bus

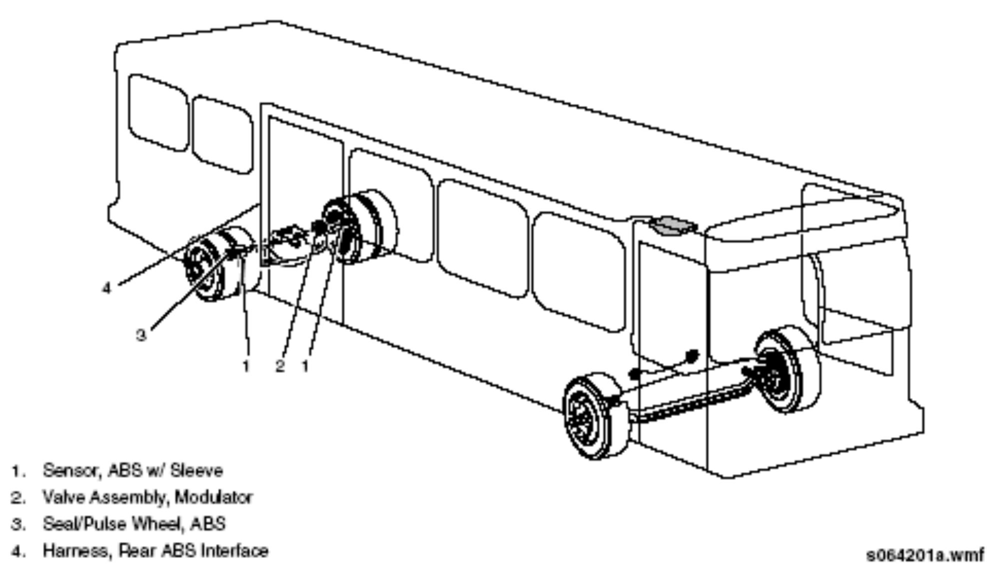


Figure 8.9 ABS System of New Flyer 40' CNG bus

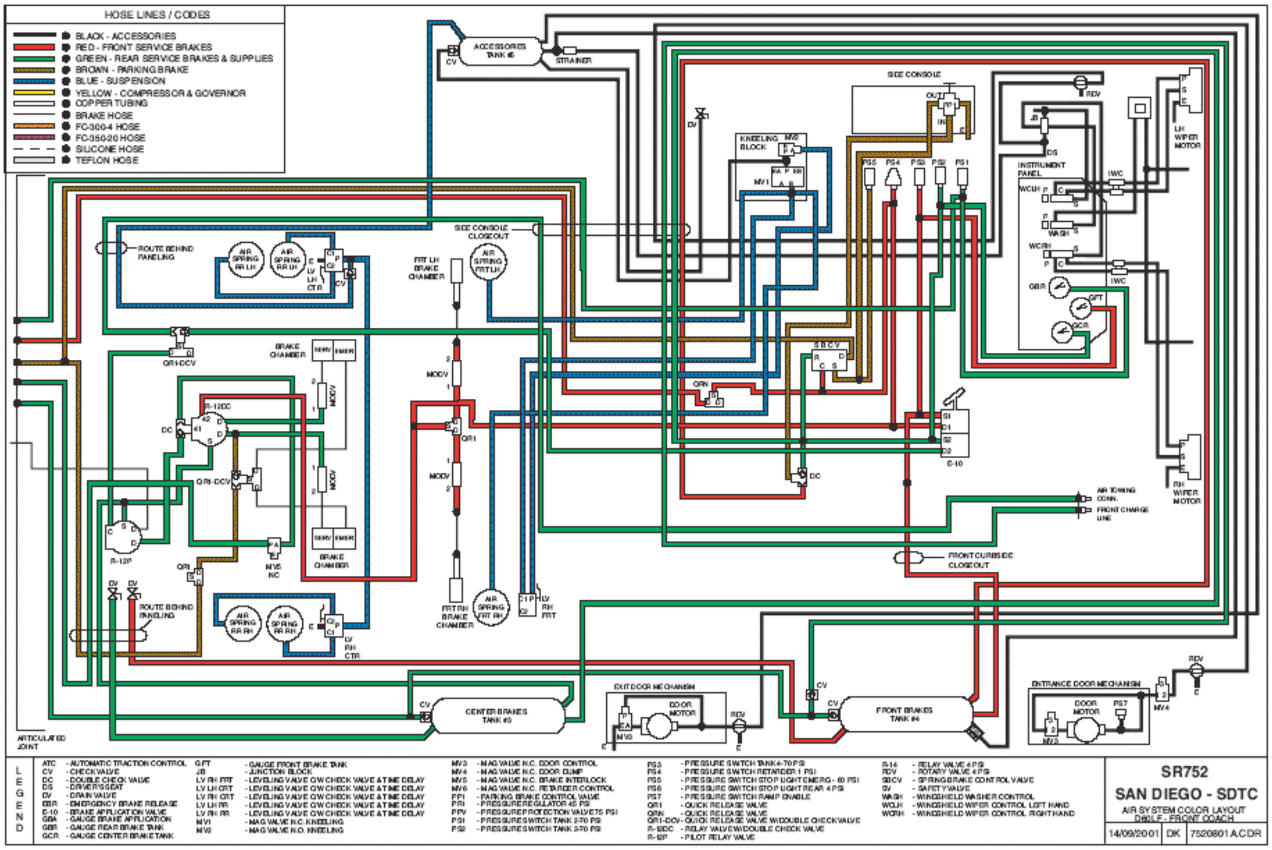


Figure 8.10 Compressed Air System of New Flyer 60' Diesel Bus

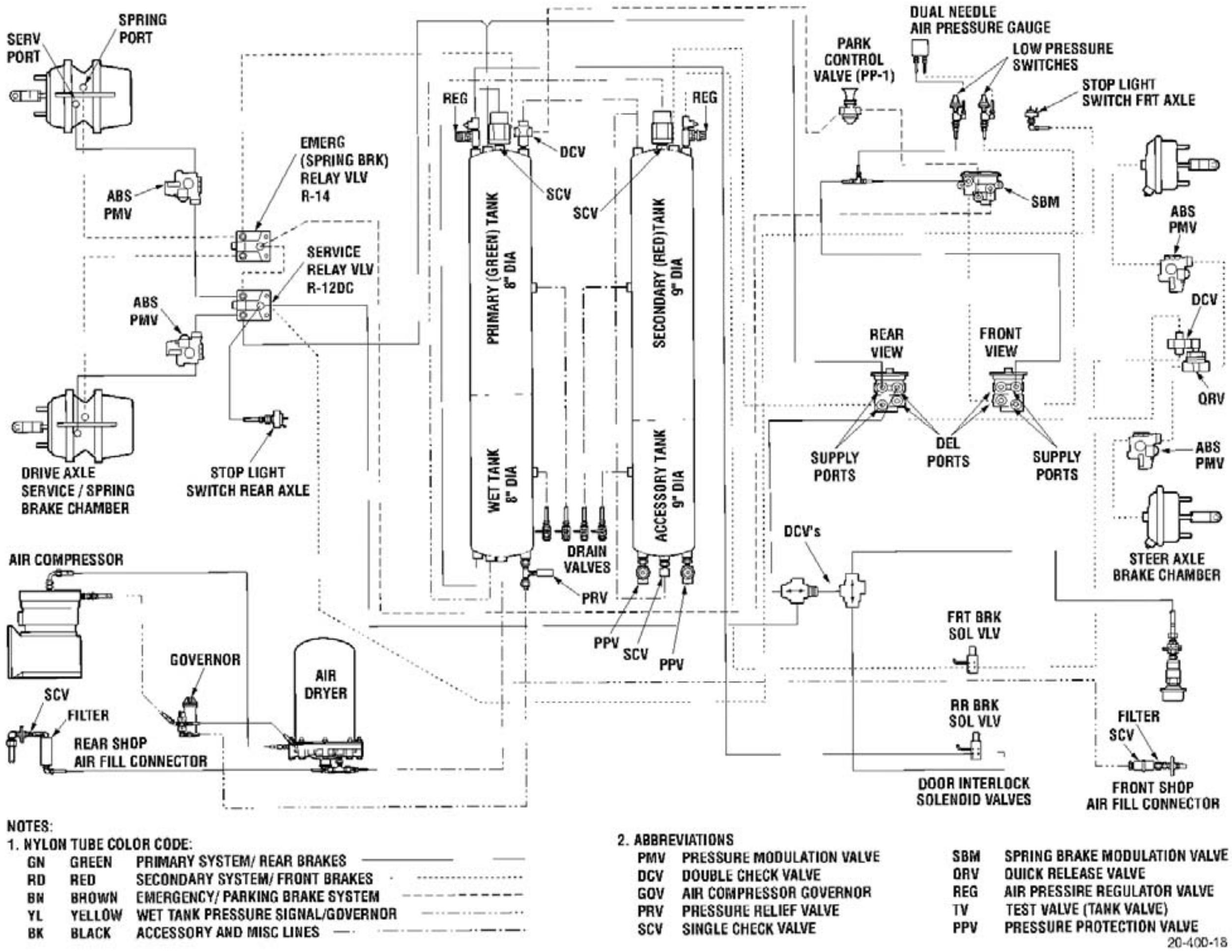


Figure 8.11 Pneumatic Brake System of Gillig 40' Low Floor

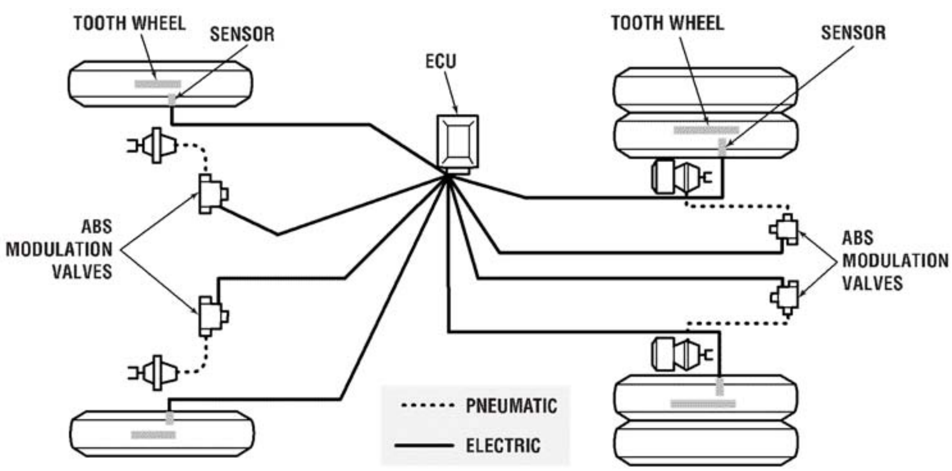
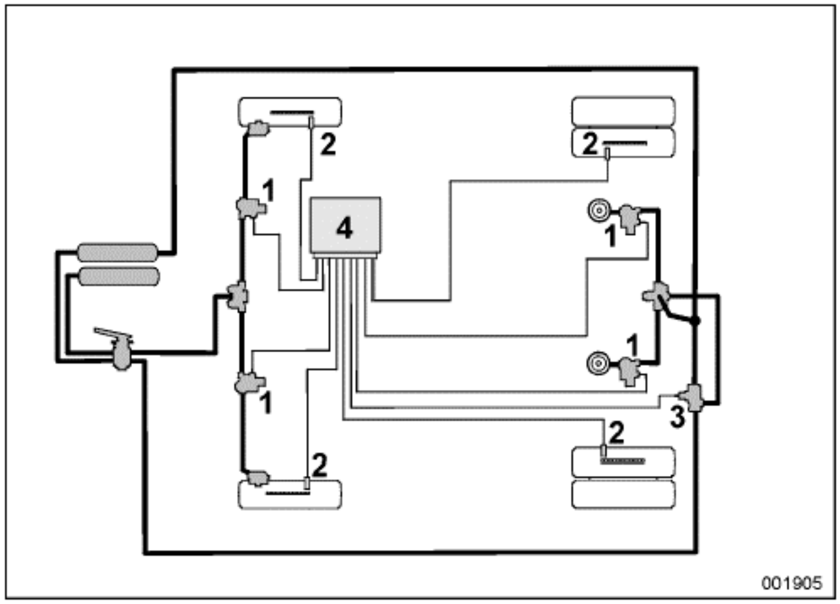


Figure 8.12 ABS Brake System of Gillig 40' Low Floor



1 ABS valve
2 Wheel-speed sensor
3 ASR valve
4 Electronic controller

Figure 8.13 Schematic of ABS and ASR System on VanHool Buses

8.6 Appendix F Implementation of data communication on testing bus

Table 8.1 Messages sent from Sensor Computer to Control Computer

PGN	MSG NAME	FIELD	BYTES	RANGE	SCALING	UPDATE
255,16	LAI_CTRLSTAT input to lateral control *from LAT_CONTROL_ INPUT*	steer_angle ready	0-3 4	-1440.000 - +1440.000 0-255	*1000	20 ms
		actuator_status	5	0-255		
		fault_code	6	0-255		
		unused	7			
255,17	LAI_STIN input from steering servo to tdriver (debug) *from LAT_STEER_ INPUT*	steer_angle	0-1	0.00-10.00V	*100	50 ms
		driver_status	2	0-255		
		failure_code	3	0-255		
		counta	4-5	0-65535		
		unused	6-7			
255,18	LAI_STOUT output from tdriver to steerctl (debug) *from LAT_STEER_ OUTPUT*	torque	0-1	0.5-4.5V	*10000	50 ms
		mode	2	0-255		
		unused	3-7			
255,19	LAI_LATOUT output from steerctl to hardware (debug) *from LAT_OUTPUT*	torque	0-1	0.5-4.5V	*10000	50 ms
		clutch	2	0-255		
		unused	3-7			
255,20	LAI_SIGSTAT input to lateral control *from SIGNALPROC_ OUTPUT*	mag_health	0-1	0-16383		20 ms
		mag_dist	2-3	0.00-100.00	*100	
		f_sensor	4 (bits 0-2)	0-7 (LL to RR)		
		r_sensor	4 (bits 3-5)	0-7 (LL to RR)		
		current_gear	5			
		wheel_speed	6-7	0.00-70.00 m/s		
255,21	LAI_SIGOUT input to lateral control *from SIGNALPROC_ OUTPUT*	delta_timer_obs	0	0-1023 ms	/4	20 ms
		f_ymeas	1-2 (bits 0-3)	-2.000-2.000m	*1000	
		f_ycar	2 (bits 4-7) - 3	-2.000-2.000m	*1000	

		f_mark_flag	4 (bits 0 - 1)	-1,0,1,2		
		f_polarity	4 (bit 2)	0-1		
		r_mark_flag:	4 (bits 3-4)	-1,0,1,2		
		r_polarity	4 (bit 5)	0-1		
		r_ymeas	5 - 6 (bits 0-3)	-2.000-2.000m	*1000	
		r_ycar	6 (bits 4-7) - 7	-2.000-2.000m	*1000	
255,22	LAI_GYRO *from GYRO*	rate	0-3	-60.00000 to 60.00000 deg/s	*100000	50 ms
		unused	4-7			
255,23	LAI_DVIMON from DVI computer *from DVI_MONITOR*	mode	0	0-255		50 ms
		unused	1-7			
255,24	LAI_LATSENS lateral sensors input *from LAT_INPUT_ SENSORS*	lat_acc	0-1	0-10.00V	*100	20 ms
		long_acc	2-3	0-10.00V	*100	
		manual_trans	4 (bit 0)	0-1		
		auto_trans	4 (bit 1)	0-1		
		auto_steer	4 (bit 2)	0-1		
		auto_throt	4 (bit 3)	0-1		
		auto_brake	4 (bit 4)	0-1		
		dc1	4 (bit 5)	0-1		
		dc2	4 (bit 6)	0-1		
		unused	5-7			
255,25	LAI_LONGIN1 longitudinal sensors *from LONG_INPUT*	acc_pedal	0-1	1.00-10.00V	*100	20 ms
		fb_axle	2-3	1.00-10.00V	*100	
		rb_axle	4-5	1.00-10.00V	*100	
		unused	6-7			
255,26	LAI_LONGIN2 longitudinal sensors *from LONG_INPUT*	fp_applied	0-1	1.00-10.00V	*100	20 ms
		rb_applied	2-3	1.00-10.00V	*100	
		fb_monitor	4-5	0.00-10.00V	*100	
		rb_monitor	6-7	0.00-10.00V	*100	

Table 8.2 Messages sent from Control Computer to Sensor Computer

PGN	MSG NAME	FIELD	BYTES	RANGE	SCALING	UPDATE
255,32	LAI_DVISTAT lateral control status for DVI display *to LAT_DVI_ OUTPUT and DVI_LEDS*	steer_fault	0 (bits 0-3)	-6 to 2		20 ms
		mag_status	0 (bits 4-5)	0-1-2		
		lane_id	0 (bits 6-7)	0-1-2		
		overall_mode	1	0 to 47		
		platoon_info	2	0-1-2-3-4		
		lat_status1	3	0-1		
		lat_status2	4	0-1		
		lat_status3	5	0-1-2		
		lat_status4	6	0-1-2		
		red	7 (bit 0)	0-1		
		green	7 (bit 1)	0-1		
		blue	7 (bit 2)	0-1		
		amber	7 (bit 3)	0-1		
255,33	LAI_DVISND DVI sounds *to DVI_LEDS*	sound1	0-1	0-10.00V	*100	20 ms
		sound2	2-3	0-10.00V	*100	
		sound3	4-5	0-10.00V	*100	
		sound4	6-7	0-10.00V	*100	
255,34	LAI_DVIPOS lateral position info for DVI display *to LAT_DVI_OUTPUT*	lat_pos	0-1	-200->200		20 ms
		long_pos	2-3	0-120		
		distance_end	4-5	0-11102		
		lat_est	6-7	-720->720		
255,35	LAI_CTRLOUT output to tdriver *to LAT_CONTROL_ OUTPUT*	steer_ctrl	0-3	-1440.000 to +1440.000	*1000	20 ms
		actuator_mode	4	0-255		
		steer_mode	5	0-255		
		unused	6-7			
255,36	LAI_LATHEART *to LAT_HEARTBEAT_ OUTPUT*	is_active	0	0-1		25 ms
		unused	1-7			
255,37	LAI_LONGOUT *to LONG_OUTPUT*	acc_pedal_ctrl	0-1	0-10.00V	*100	20 ms
		fb_ctrl	2-3	0-10.00V	*100	
		rb_ctrl	4-5	0-10.00V	*100	
		unused	6-7			