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TCRP Report 43

Understanding and Applying Advanced On-Board Bus Electronics

Transportation Research Board
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TRANSIT COOPERATIVE RESEARCH PROGRAM

Report 43

Understanding and Applying Advanced On-Board Bus Electronics

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Subject Area

Public Transit

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TRANSIT COOPERATIVE RESEARCH PROGRAM

The nation's growth and the need to meet mobility, environmental, and energy objectives place demands on public transit systems. Current systems, some of which are old and in need of upgrading, must expand service area, increase service frequency, and improve efficiency to serve these demands. Research is necessary to solve operating problems, to adapt appropriate new technologies from other industries, and to introduce innovations into the transit industry. The Transit Cooperative Research Program (TCRP) serves as one of the principal means by which the transit industry can develop innovative near-term solutions to meet demands placed on it.

The need for TCRP was originally identified in *TRB Special Report 213--Research for Public Transit: New Directions,* published in 1987 and based on a study sponsored by the Urban Mass Transportation Administration--now the Federal Transit Administration (FTA). A report by the American Public Transit Association (APTA), *Transportation 2000,* also recognized the need for local, problem-solving research. TCRP, modeled after the longstanding and successful National Cooperative Highway Research Program, undertakes research and other technical activities in response to the needs of transit service providers. The scope of TCRP includes a variety of transit research fields including planning, service configuration, equipment, facilities, operations, human resources, maintenance, policy, and administrative practices.

TCRP was established under FTA sponsorship in July 1992. Proposed by the U.S. Department of Transportation, TCRP was authorized as part of the Intermodal Surface Transportation Efficiency Act of 1991 (ISTEA). On May 13, 1992, a memorandum agreement outlining TCRP operating procedures was executed by the three cooperating organizations: FTA; the National Academy of Sciences, acting through the **Transportation Research Board (TRB);** and the Transit Development Corporation, Inc. (TDC), a nonprofit educational and research organization established by APTA. TDC is responsible for forming the independent governing board, designated as the TCRP Oversight and Project Selection (TOPS) Committee.

Research problem statements for TCRP are solicited periodically but may be submitted to TRB by anyone at any time It is the responsibility of the TOPS Committee to formulate the research program by identifying the highest priority projects. As part of the evaluation, the TOPS Committee defines funding levels and expected products.

Once selected, each project is assigned to an expert panel, appointed by the Transportation Research Board. The panels prepare project statements (requests for proposals), select contractors, and provide technical guidance and counsel throughout the life of the project. The process for developing research problem statements and selecting research agencies has been used by TRB in managing cooperative research programs since 1962. As in other TRB activities, TCRP project panels serve voluntarily without compensation.

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The TCRP provides a forum where transit agencies can cooperatively address common operational problems. The TCRP results support and complement other ongoing transit research and training programs.

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The members of the technical advisory panel selected to monitor this project and to review this report were chosen for recognized scholarly competence and with due consideration for the balance of disciplines appropriate to the project. The opinions and conclusions expressed or implied are those of the research agency that performed the research, and while they have been accepted as appropriate by the technical panel, they are not necessarily those of the Transportation Research Board, the National Research Council, the Transit Development Corporation, or the Federal Transit Administration of the U.S. Department of Transportation.

Each report is reviewed and accepted for publication by the technical panel according to procedures established and monitored by the Transportation Research Board Executive Committee and the Governing Board of the National Research Council.

To save time and money in disseminating the research findings, the report is essentially the original text as submitted by the research agency. This report has not been edited by TRB.

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FOREWORD

By Staff
Transportation Research Board

TCRP Report 43, "Understanding and Applying Advanced On-Board Bus Electronics" will be of interest to transit managers, operations and maintenance professionals, bus procurement specialists, bus manufacturers and suppliers, and others interested in the application of advanced electronics to transit buses. The report provides an overview of electronics and its application to buses and other transportation sectors. The report then addresses electronic integration, potential benefits offered by integration, and transit agency experiences with the technology. The report concludes with guidelines for implementing transit bus electronics. It is intended to be a primer on the subject, providing essential background information to serve as a starting point for acquiring additional knowledge.

The vast amount of electronics being incorporated into transit buses needs to be integrated in a way that takes full advantage of the technology. Advanced electronic systems have the ability to work together to perform a variety of functions to enhance bus operations, monitor equipment performance, diagnose technical problems, and provide important data to improve service efficiency and reduce operating costs. However, before such advantages can be realized, the industry needs to understand how electronic on-board systems function; determine the benefits such systems can offer; establish a standardized approach to system integration, data collection, and dissemination; and identify implementation requirements.

Under TCRP Project C-10A, research was undertaken by John J. Schiavone to (1) provide a basic level of understanding concerning advanced electronics and its application to transit buses; (2) describe how the application of electronics to individual components has improved their functionality; (3) describe how individual components can be integrated into larger systems to provide potentially greater benefits; (4) describe the experiences of a representative sampling of transit agencies that have integrated, or are planning to integrate, electronic technologies; and (5) offer a set of guidelines to (a) help transit managers and maintenance personnel decide if a given technology is appropriate for their operations, (b) plan procurement strategies for vehicles or components using advanced electronics, (c) prepare maintenance and training programs, (d) take full advantage of the technology's capabilities, and (e) manage the data generated from the equipment.

To achieve the project objectives, the researcher obtained information from a variety of sources, including 19 transit agencies employing various types of advanced onboard bus electronics. In addition, approximately 45 other relevant organizations were contacted, including bus manufacturers, suppliers, government agencies, and trade associations. A review of relevant technical literature was also conducted.

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The author acknowledges the valuable contributions made by representatives from transit agencies, bus and component manufacturers, systems integrators, and others who provided information for this report. Constructive assistance was also provided by individual Panel members and TCRP Program Officer Christopher Jenks.

CONTENTS

EXECUTIVE SUMMARY

Bus transit has entered a new era — the electronic era where equipment brings with it a new set of capabilities and challenges. This study provides a basic level of understanding to assist transit managers make better use of the technologies and to address the challenges.

The application of advanced on-board electronics has evolved in stages. Simple electronics such as transistors are first applied to improve the functionality and longevity of individual components. Electronics are then incorporated into control modules or "black boxes," capable of manipulating data to exert greater control over equipment. Electronic controls also have the ability to:

- Make data available to technicians to assist with diagnostics;
- Share data with other on-board equipment to collectively accomplish tasks that no single component could achieve individually;
- Transfer data back to the transit agency in real time to monitor operator, vehicle, and mechanical performance; and
- Store data for retrieval at a later time for further analysis.

The integration of electronic components has developed around three bus areas:

- Drivetrain Level where the engine, transmission, brakes and other components exchange data to improve driveability and safety;
- Electrical Level where the on/off nature of "hotel" devices such as lights and small electrical motors are controlled by a computer-based multiplexing system to streamline the electrical system for reduced complexity and bus weight; and the
- Information Level where radio communication, vehicle location, fare collection, passenger information, passenger counting, and other systems are integrated to improve the efficiency of moving passengers and the agency's own operation.

Each bus level has taken a separate approach to integration, which requires a data network based on specified rules or "protocols" to exchange data. A data network provides a framework whereby all components linked to the system speak and understand the same electronic language.

Electronic integration has evolved around three bus levels because there was, and still is, no practical network capable of joining all bus components into a single "system." Although integration is divided into three levels, gateway devices capable of translating electronic languages can be used to exchange data between levels.

In general, the networks used to integrate electronic components can be based on open or proprietary protocols. An open data communication protocol lies in the public domain, allowing any manufacturer to build components to comply with defined rules. Proprietary networks restrict network access to those licensed to use it. While open networks promote product interchangeability, proprietary networks tie users to specific products and limit choice.

The integration of Drivetrain Level components follows requirements established by the Society of Automotive Engineers (SAE) specifically for truck and bus applications. The requirements are formalized in a series of data networks (called standards) based on open communication protocols. J1708 was the first SAE standard used to integrate drivetrain components, followed by the more robust J1939 network needed to handle the complexity of anti-lock brakes and traction control. Every bus delivered to U.S. transit agencies today uses SAE data networks for drivetrain integration.

Electrical Level integration (i.e., multiplexing) is based on proprietary networks developed by firms specializing in machinery automation and aerospace technology. Since they are used primarily to control simple on/off type functions, the proprietary nature of the operating system itself does not affect the device being controlled. As a result, agencies can continue to purchase lamps, electric starter motors, and related switches from traditional sources.

Information Level integration is currently in a state of transition regarding the use of data networks. SAE J1708, modified to suit bus applications, is beginning to be specified by some agencies. In the past, however, systems were designed around proprietary networks.

While many support a vehicle area network (VAN) for Information Level integration based on J1708, others feel that it is too slow to handle data transfer to and from the agency in real time. Proponents of J1708 claim the radio is the limiting factor and, after evaluating several alternatives, have determined that J1708 is the most appropriate solution for bus applications. As the controversy continues, provisions in Transportation Equity Act for the 21st Century (TEA 21) may require provisional standards if transportation modes cannot decide on one.

Issues concerning on-board data exchange have also impacted heavy-duty trucking and rail transit. Through a Transportation Research Board (TRB) project, rail transit is developing a standardized approach to on-board data communication. More closely allied with buses is the truck, which serves as a model for electronic integration. A modern truck has about 10 computer-controlled systems, including vehicle location, radar crash avoidance, radio communication, equipment monitoring, and others. Like the drivetrain, each system exchanges data using a SAE J1708-based network. The approach gives fleet owners a variety of products to choose from, and saves the truck builder engineering time when accommodating the individual needs of fleet operators.

The trucking industry has progressed to the point where Information Level components are integrated into the overall vehicle design. With regard to transit buses, the integration is typically accomplished as retrofits to accommodate the many buses already in the fleet. In time, however, bus builders will need to take a more active role in designing their vehicles to accept this equipment as integral part of its design.

Electronic integration has the potential to provide many benefits. Some benefits are more "automatic" than others, coming to the agency with little if any effort. Examples include the many benefits offered by drivetrain and electrical system integration. For example, the engine, transmission, and retarder work in unison to improve driveability without requiring much intervention by the agency (i.e., up-front engineering or specification work). Multiplexing is also delivered to the agency as a complete system, engineered into the bus to streamline its electrical system.

Unlike drivetrain integration and multiplexing, Information Level components such as radio communication, vehicle location, fare collection, passenger information, and passenger counting systems are typically integrated into the bus after it is built. This retrofitting aspect requires agencies to invest a great deal of effort if tangible benefits are to be obtained. At one agency, the technical specification alone for its new radio and automatic vehicle location (AVL) system consists of nearly 400 pages.

Information Level integration is complex. Due to its virtual unlimited potential, agencies and vendors alike are continually finding new ways to apply the technology and reap benefits from it.

Applications have provided several significant benefits. Included are improved operator-to-agency communication, monitoring of key vehicle and operator performance indicators, improved passenger information,and fare data based on individual transactions.

While many successes have been actively promoted, comprehensive cost/benefit analyses to objectively access the value of these benefits are not yet complete. Furthermore, the many downside aspects to the implementations, caused by the technology and agencies applying it incorrectly, have been minimized. They include insupportable equipment, legal disputes, procurement delays, agencies receiving outdated equipment, and new equipment that does not perform as originally intended.

The ability to successfully implement Information Level technologies depends on many factors, including the agency's ability to:

- Thoroughly understand the technology and related issues;
- Develop a long-range plan that applies technology in a systematic manner to address specific needs;
- Write a specification that clearly identifies agency needs and how the technology is expected to address those needs;
- Train the staff to operate and maintain the equipment properly, and to deal with on-going software development programs to maximize the hardware's effectiveness;
- Anticipate the costs and organizational effort required to implement the technology;
- Manage all of the data generated from the integration;
- Use open data communication protocols to ensure product interchangeability, system expansion, and product availability;
- Understand that advanced equipment will have a limited shelf-life due to new technology advances and future industry standards and regulations; and
- Ensure that suppliers will provide adequate service and product support for the life of the equipment.

The need to have the above-mentioned factors in place cannot be overemphasized. The complexity and level of effort needed to apply Information Level technologies will test the ability of individual agencies, as well as the entire industry, to produce quantifiable benefits. To help meet this challenge, this study offers the following guidance to bus transit:

- Promote the understanding of electronic technologies and related issues in terms that the entire industry can comprehend;

- Create frank and open forums to objectively address and communicate all aspects of the technology, related issues, and experiences;
- Encourage bus builders to incorporate Information Level equipment into the overall vehicle design as is done in the automobile and trucking industries;
- Settle the controversy that exists over the SAE J1708-based VAN and adopt a suitable on-board standard for data exchange as quickly as possible to avoid the potential mandating of standards by TEA 21;
- Encourage additional agency representation espcially from maintenance and operations, in the standards-development process to ensure that standards are, and continue to be, appropriate for bus transit;
- Determine how data generated from Information Level equipment can be used to benefit all agencies;
- Establish a peer review panel comprised of experienced bus transit representatives to review and assist transit agencies during planning and implementation phases;
- Consider expanding "White Book" specifications to create a standardized approach to electronic integration where data cables, plug-in component receptacles, and the communication protocol that on-board electronic components use to communicate are stipulated for use in a uniform and efficient manner; and
- Create an environment where agencies, suppliers, relevant government agencies, trade associations, and others all work in unison to provide the "organizational horsepower" needed to ensure that electronic integration provides quantifiable benefits in the most cost-effective manner possible.

INTRODUCTION AND RESEARCH APPROACH

Electronics — no other technology has contributed more to the increased functionality and complexity of transit buses. When the Advanced Design Bus (ADB) was introduced in the late 1970s, solid state voltage regulators, alternator diodes and fluorescent lighting were virtually the only examples of on-board electronics. Fareboxes and destination signs with electronic controls appeared shortly afterwards as optional equipment. Today, electronics has become an integral part of every bus. Moreover, recent advances make it possible to combine electronic components and systems in unique and complex ways, providing benefits not possible with individual components.

Using electronics to combine or "integrate" components has the potential to help revitalize bus transit by offering passengers an enhanced level of service to compete with other transportation modes. However, as transit enters this new era of electronic application, it must address a new set of challenges if the technology is to succeed.

For one, the complexity involved with electronic integration can be confusing and difficult to keep pace with, especially for those accustomed to mechanical systems. The complexity is reduced when the bus builder integrates the equipment. For example, electronic drivetrain components are delivered as a fully integrated system. Integration of "information" components such as advanced radio and automatic vehicle location (AVL) systems, however, typically takes place after the bus is assembled. This retrofitting aspect requires a great deal of involvement and understanding by the transit agency if the system as a whole is to provide tangible benefits.

The need to understand thoroughly how evolving electronic technology can be applied to solve problems and enhance service cannot be overstated. Lack of understanding could hamper the technology's introduction, making it difficult to take full advantage of its capabilities, develop adequate maintenance programs, plan procurement strategies, initiate new training, and manage data generated by the equipment.

Another important challenge facing bus transit is the lack of industry-accepted standards to integrate the technology. While drivetrain integration has been standardized, other on-board devices are typically built around proprietary systems that often lock agencies into single suppliers and restrict interoperability.

Despite the "maintenance free" label given to electronics, components are bound to fail at times, especially when subjected to 12 or more years of bus service. Dirty conditions caused by constant passenger traffic and interior vacuums, vibration, moisture, fumes, and in some cases low-skilled technicians and inadequate specifications, can wreak havoc with electronics. When electronic systems do fail, untrained technicians will require new skills and tools to diagnose faults.

Fluctuations in funding can impede an agency's ability to provide the tools and skills needed to maintain on-board electronics. Inconsistent funding could also prevent agencies from implementing technology on a fleet-wide basis, leaving some buses without essential equipment. Additionally, lengthy procurement cycles can exacerbate the problem of technology becoming quickly outdated.

Of all the challenges facing transit today, converting the vast amount of data produced by on-board electronic equipment into useful information is arguably the most significant. Speaking at the 1997 APTA Annual Meeting, futurist Frank Feather stated "... In this new society, transit isn't about moving people. Now it's about managing and moving information about moving people." He emphasized that unless transit professionals keep up with the current technology they will become "roadkill on the information superhighway" (1). Although somewhat overstated, the point is clear — electronic technologies produce additional information that must be managed.

The many opportunities and challenges brought forth by the proliferation of bus electronics can be attributed to four major factors:

(1) The technology, much of which has proven itself reliable and beneficial in other transportation applications, is readily available and transferable for bus use.

(2) Agencies continually seek new bus features to benefit passengers, bus operators and their own operations and maintenance departments.

(3) Federal regulations calling for:

  a) the reduction of heavy-duty diesel exhaust emissions (Environmental Protection Agency - EPA);

b) improved on-board communications to allow disabled passengers to be oriented to their destination (Americans with Disabilities Act - ADA); and

c) anti-lock brake systems (ABS) (Federal Motor Vehicle Safety Standards - FMVSS).

(4) Passage of the Intermodal Surface Transportation Efficiency Act of 1991 (ISTEA), creating formal programs for Intelligent Transportation Systems (ITS) and Advanced Public Transportation Systems (APTS); and the Transportation Equity Act for the 21st Century (TEA 21), which continues ITS programs.

Much of the advanced electronics being applied to transit buses today has filtered down from aerospace, military and commercial aviation applications. The automobile industry, using motor racing as its test bed, was a pioneer in the development of advanced electronics for on-highway use. Today, automobiles have more computer power than the original Apollo spacecraft. Further, the use of electronics in auto racing has become so extensive that sanctioning bodies limit technology in some classes to shift the competitive emphasis back to human ability.

A few observations made from the use of electronics and computers in auto racing provide an interesting perspective to those in bus transit looking to apply the technology (2):

(1) There is no magic. Computers are tools invented, designed, manufactured and used by humans to do ordinary tasks quicker and easier.

(2) Computers do not replace humans. In fact, they have increased the number of people required to manage the additional information made possible by computers.

(3) It is computer software that really matters. Hardware consists of relatively simple and available components — the software is where the bulk of human creativity comes to bear.

OBJECTIVES

For many in bus transit, gaining an understanding of advanced electronics is not an easy task. Available material tends to be narrowly focused around specific products and topics, making it difficult to grasp the entire subject. Additionally, much of the material promotes a particular product or program, making it difficult to obtain an unbiased viewpoint.

The objectives of this study are to:

(1) Provide a basic level of understanding concerning advanced electronics and its application to transit buses.

(2) Describe how the application of electronics to individual components has improved their functionality.

(3) Describe how individual components can be integrated into larger systems to provide potentially greater benefits.

(4) Describe the experiences of a representative sampling of transit agencies that have integrated, or are planning to integrate, electronic technologies.

(5) Offer a set of guidelines to assist transit managers and maintenance personnel:

a) decide if a given technology is appropriate for their operation;

b) plan procurement strategies for vehicles or components using advanced electronics;

c) prepare maintenance and training programs;

d) take fuller advantage of the technology's capabilities; and

e) manage the data generated from the equipment.

APPROACH

The subject of electronics and its application to buses is extremely complex. This study is intended as a primer on the subject, providing essential background information to serve as a starting point for acquiring additional knowledge.

Information presented in this study was obtained-from a variety of sources including technical literature, telephone contacts, and site visits made to selected transit agencies and equipment suppliers. Due to its comprehensive nature, this study did not attempt to include the experiences of every transit agency. It does, however, provide a representative sampling of experiences to help guide others with their implementation efforts. A listing of transit agencies visited and contacted for this study is included in Appendix A.

ORGANIZATION

This study begins by providing essential overview material on electronics and its application to buses and other transportation sectors. Later chapters address electronic integration, potential benefits offered by integration, and transit agency experiences with the technology. The study concludes with a set of guidelines for implementing on-board electronics.

To assist those seeking general information, each chapter begins with a summary that provides essential overview material. The summaries furnish a "big picture" look at the subject before addressing the details. They also provide an abbreviated method of reading the document.

The study is organized as follows:

Chapter 1 addresses electronics in general terms and reviews the five stages of electronic application to buses.

Chapter 2 describes how electronics has enhanced the functionality of specific bus components.

Chapter 3 reviews electronic applications to other vehicles including automobiles, trucks and rail transit.

Chapter 4 describes multiplexing, which uses proprietary data networks to integrate the control of basic on/off-type switching functions in the electrical system.

Chapter 5 describes how standard data networks developed by the Society of Automotive Engineers (SAE) can be applied to integrate equipment in the Drivetrain and Information Levels.

Chapter 6 summarizes key programs that support electronic integration including ITS, and programs that promote the exchange of data between ITS elements.

Chapter 7 takes a broad look at the potential benefits that agencies can hope to achieve from electronic integration.

Chapter 8 examines the experiences of a representative sampling of transit agencies applying electronics to buses.

Chapter 9 takes all of the material gathered from the study and offers guidelines to consider when implementing on-board electronics.

CHAPTER 1

ELECTRONICS: OVERVIEW AND APPLICATION

This chapter provides an overview of electronics and its application to buses. Highlighted are the many advances made in a relatively short period of time.

SUMMARY

Before addressing electronics, a distinction must be made between "electrical" and "electronic." An electrical system consists of (1) the framework that carries electrical battery current throughout the bus, and (2) the various devices that utilize that current. The electrical framework includes the batteries, wiring, wire connectors, relays and switches. Examples of electrical devices include incandescent lights, passenger stop chime, the engine's starter motor, and heating/ventilation fan motors.

To control these electrical devices, a series of electro-mechanical switches called relays are energized in response to an operator's command or other triggering action. For example, placing the gearshift lever in reverse energizes a relay that sends electrical current to the reverse lamps. Known as relay logic, the system requires individual hard wires traveling to relays and each device being controlled. As the number of control functions increased and became more complex, relay logic was found to be inadequate.

Electronic controls replace relay logic with solid state components that share information in serial data streams. The result is less wiring and the ability to control functions more efficiently. Electronics is an out-growth of the transistor, invented in 1947 as a means of switching electrical power without moving parts, thus the term "solid state." Solid state electronics was first applied to improve the functionality of specific components. For example, the addition of solid state electronics to alternators and voltage regulators improved battery charging.

While the transistor was significant, it was the invention of the integrated circuit (IC) in 1958 that led to the commercialization of electronic products. Before the IC, there was no practical way of combining the myriad of components such as transistors, diodes and resistors into a cohesive package. The miniaturization of IC "chip technology" eventually led to the development of solid state control systems such as microprocessors and computers.

Packaged into what is referred to as electronic control modules (ECMs), ICs enable components to be controlled with increased speed, improved reliability and less power. Today, ECMs or "black boxes" enhance the operation of virtually every major bus system and accessory. ECMs are also capable of self calibration, self diagnostics and data storage — characteristics not possible with mechanical controls.

Fareboxes, destination signs, engines and transmissions were among the first bus components to apply electronic controls. Doors, multiplexed wiring systems, anti-lock brakes (ABS), air conditioning, automatic vehicle location (AVL) and other equipment followed.

As the evolution of electronics progressed, components were integrated into larger systems capable of performing more complex tasks because of their ability to share data. Component integration was made possible by the creation of data networks, a framework which establishes the protocol or "electronic language" that components use to exchange data.

In the next stage of on-board electronic development, data produced from components are transmitted to remote locations. This transfer of data can occur through a physical plug connection or radio frequency (RF) transmission. AVL systems, originally developed to monitor bus location, have been expanded to collect data from several on-board systems and broadcast that data to the transit agency and other locations.

In a future stage of electronic application, powerful computers using artificial intelligence will exert greater control over vehicles, such as radar-assisted steering and other vehicle control functions.

ELECTRONICS: THE SECOND INDUSTRIAL REVOLUTION

The impact that electronics has had on nearly every facet of our life today would not be possible without the invention of the transistor in 1947 (3), and the integrated circuit (IC) in 1958 (4, 5). The transistor is a compact device used to switch direct current (DC) power, the type of electrical power used in transit buses. Transistors perform silently and have no moving parts — hence the term "solid state." As a replacement for vacuum tubes, the transistor offered many advantages including reduced size and weight, rugged char-

Parameter	**ENIAC 1946**	**IBM PC-AT 1985**	**IBM ThinkPad 770 Notebook 1997**
Size	3,000 Ft.^{3}	1.35 Ft.^{3}	0.16 Ft.^{3}
Power Consumption	140,000 Watts	140 Watts	20 a
Program Storage	16K Bits	40 Megabytes	5,000 Megabytes
RAM	1K Bits	6K Bytes	32 Megabytes
Clock Rate	1 Megahertz	6 Megahertz	233 Megahertz
Weight	60,000 lbs.	50 lbs.	7.8 lbs.

Table 1-1 ***Comparison of the 1946 ENIAC vacuum tube computer with a PC of the mid 1980s, and today's notebook PC.***

acteristics, long life, and the ability to operate at lower voltages with higher efficiency.

An IC is the general term used to describe the grouping of many electronic components (e.g., transistors, resistors, and diodes) into an extremely small space. ICs are classified by the number of elements they contain. A very large scale integrated circuit, for example, accommodates about 7.5 million elements in a space of about one square inch.

The development of the IC was important and timely because without it, the commercialization of solid state electronics would not be possible. Prior to the IC there existed no practical way of connecting the many electronic components in a compact, reliable and cost-effective package. The ongoing development and commercialization of solid state technology has become known as the "Second Industrial Revolution" or the "Electronic and Information Revolution."

Circuit Integration Reduces Size, Increases Speed

Since first introduced over 30 years ago, ICs have become integrated into smaller and smaller units. What once was housed in large mainframes now fits into the palm of a hand. Each reduction in size has increased the speed of operation, improved reliability, and decreased power requirements.

The advancement of ICs can be illustrated by comparing the pre-transistor ENIAC vacuum tube computer of 1946 to personal computers (PCs) of the 1980s, and portable PCs of the 1990s. As Table 1-1 illustrates, the ENIAC of 1946 is no match for today's portable computer. Based on the electronic advances made during the past 50 years, one can only imagine what will transpire during the next half century.

Microprocessors and Memory

The miniaturization of ICs, also referred to as "chip technology," produced two key elements essential to the development of solid state control systems: microprocessors and memories (6). Microprocessors are essentially computers that manipulate data using binary digits, or bits.

A bit is the smallest unit of memory available, representing data that only can be expressed as either on/off, true/false. A byte represents a grouping of eight bits that can store a numerical equivalent between 0 and 255. The larger numerical range expands data beyond simple on/off to include characters, analog values and text. Microprocessors typically process and store data in 16 bit groups, also known as "words."

Memory is where program and data files are stored and manipulated. There are two types of solid state memories: volatile and nonvolatile. Volatile memory can be easily altered or erased, and can be written to and read from. Without proper backup, however, power loss can destroy programmed contents. Random Access Memory (RAM) is the best known form of volatile memory. It is relatively fast and provides an easy way to create and store application programs.

Nonvolatile memory retains its contents even if power is lost and does not require a backup. Examples of nonvolatile memory include Read Only Memory (ROM), Electronically Programmable ROM (EPROM), and Electronically Erasable Programmable ROM (EEPROM).

Microcontrollers and Microprocessors

As noted earlier, the IC led to the development of the microprocessor. Concerning bus applications, a distinction must be made between "Microcontroller" and "Microprocessor." The distinction is important because each has very different capabilities.

Electronic components such as engines and transmissions are controlled by microcontrollers, also referred to as ECMs. A microcontroller is a special-purpose processor with limited capabilities, designed to support specific tasks over the life of the component.

An engine, for example, uses an ECM to "read" inputs from various sensors and execute logic as prescribed by the application program to control fuel delivery. As conditions change (i.e., the engine warms up), fuel delivery also changes to optimize performance. The use of EPROMs and EEPROMs allows the component's operating characteristics to be changed to suit specific customer needs. Despite its ability to receive and send data to other components, an engine ECM is limited to drivetrain-related tasks.

A microprocessor, on the other hand, is a general purpose processor capable of supporting a wide range of peripheral devices and software applications. Microprocessors typically run DOS, Windows or Unix as an operating system and can be programmed to handle a wide variety of tasks based on user needs.

A vehicle logic unit (VLU) is an example of a microprocessor. The VLU can be configured to interface with several systems including the radio, AVL, and drivetrain components to perform a variety of tasks.

When customizing tasks, it is important to know where the task is housed. If the task is located within a device (i.e., ECM), functions are limited and custom applications may be restricted. Although an engine ECM can monitor vehicle mileage to calculate fuel economy, it can not be expanded to perform next-stop annunciator functions. As a general-purpose microprocessor, however, a VLU can store route data and combine it with other data to make announcements at specific locations on a given route.

THE FIVE STAGES OF ELECTRONIC APPLICATION

Background

Beginning in the 1970s, an increasing number of electronic devices were installed to enhance the functionality of bus components. In addition, the basic electrical system was increasing in size as a greater number of control features such as door interlocks and automatic climate control systems were added. The method used to control these devices is known as "relay logic." At the heart of this control system is the relay, a heavy-duty switch that directs electrical current to a particular device only when certain conditions exist. For example, the relay that allows a bus to kneel is only energized when the parking brake is applied. Achieving control through relay logic depends on numerous "hardwired" wire connections, each of which offers a potential for failure.

The advanced electronics discussed in this study replace most or all the relay logic with solid state components that share information in serial data streams. Use of solid state electronics to control functions not only reduces wiring and related components, but provides a more sophisticated degree of control possibilities.

Stage 1: Simple Electronics Enhance Functionality

Solid state electronics first appeared on transit buses around the 1970s with the introduction of alternators, solid state voltage regulators, and transistorized radio communication. Adding simple electronics such as transistors and diodes (provides one-way current flow) to individual components represented the first stage of electronic development.

The progression of electronic application to buses is consistent with the five stages of development experienced in the automobile industry (7). Table 1-2 illustrates the five stages as applied to transit buses.

Stage 1	**SIMPLE**	Simple electronic features are added to improve the efficiency of vehicle components (i.e., solid state voltage regulator and transistorized two-way radios).
Stage 2	**COMPLEX**	Microcontrollers (i.e., ECMs) create new functions to further improve the functionality of individual components (i.e., electronically controlled engines, transmissions, destination signs and fareboxes).
Stage 3	**ON-BOARD INTEGRATION**	Integrated on-board electronic systems provide capabilities greater than the sum of individual sub-systems (i.e., engine, transmission and passenger door controls share information to determine vehicle speed, door position and current gear to provide safer travel and lower emissions).
Stage 4	**OFF-BOARD INTEGRATION**	On-board bus electronic systems communicate with the transit facility and other remote locations, integrating the vehicle into larger environmental systems (i.e., AVL, downloading of vehicle condition data at the service line; ITS applications for traffic signal priority, remote traveler information; etc.).
Stage 5	**"SUPER SYSTEMS"**	(Future) Integration of high-powered computers using artificial intelligence and fuzzy logic that will make the bus and its external environment more attuned and responsive to customer safety and comfort (i.e., automated steering and speed control for "hands-free" driving).

Table 1-2 The application of bus electronics shown in five stages.

Stage 2: Electronic Controllers Improve Capabilities

In the second stage of electronic application, microcontrollers (i.e., ECMs) were added to expand the control capabilities of individual components. The use of ECMs began to escalate during the 1980s with the introduction of electronic fareboxes and destination signs. Propelling electronics into the drivetrain area were increasingly stringent exhaust emission regulations for heavy-duty diesel engines. Today, ECMs are used in virtually every major bus component including engines, transmissions, air conditioning, doors, brakes, and lighting.

The benefits obtained from electronics far exceed those possible from mechanical, pneumatic, hydraulic, and electro-mechanical controls. Characteristics of electronic controls such as speed, accuracy, reliability, self-calibration, and ease of replacement simply can not be duplicated by mechanical means. Additionally, built-in diagnostic features make electronic components easier to maintain.

Figure 1-1 illustrates the evolution of bus electronics throughout the last three decades.

Stage 3: Integration Links Components Into Larger Systems

The third stage involves the integration of electronic-controlled components into larger systems to perform more complex functions, providing additional benefits to transit agencies. Integration is made possible through the use of data networks that allow individual components to "communicate" with one another. All devices connected to the network transmit and receive data from other devices, using the data collectively to sense, monitor, and control various vehicle functions. The exchange of data allows components to interact automatically without operator intervention.

One of the first examples of component integration involved the sharing of data between the engine and transmission to improve shift quality. When the transmission sends information over the network that it is about to make a gear change, the engine can momentarily reduce its torque output to make the shift a smoother one — all without operator intervention. Other examples of integration made possible by data networks include:

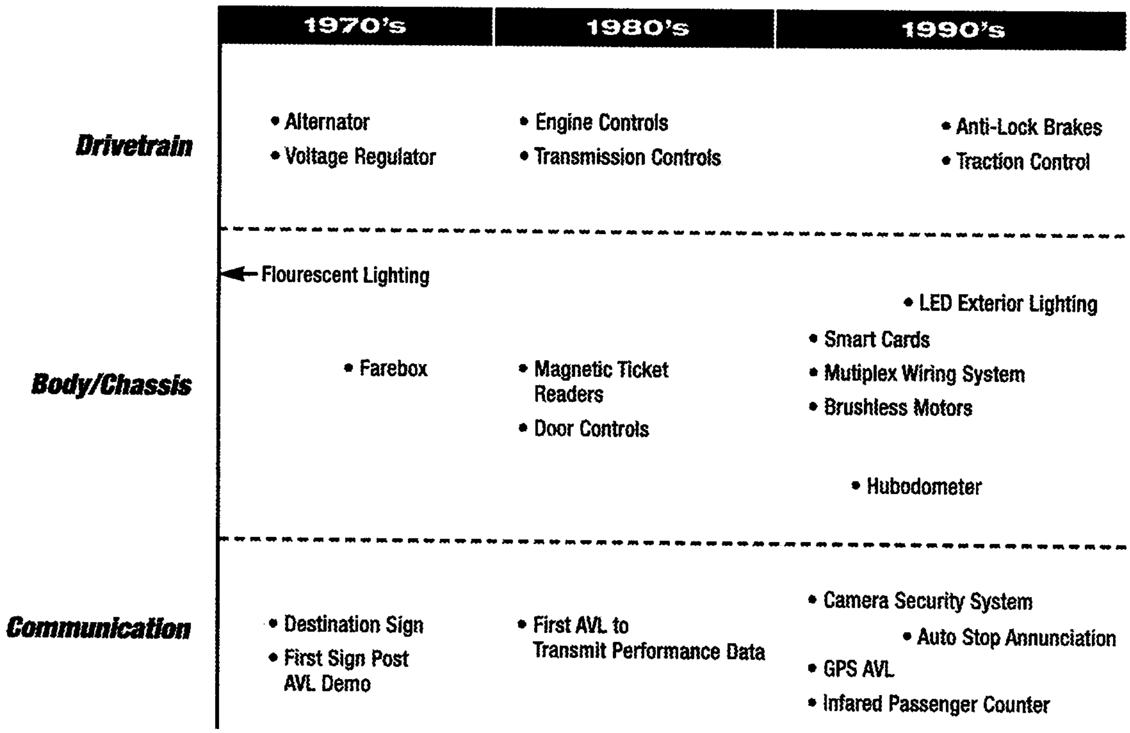

Figure 1-1 Evolution of bus electronics during the last three decades.

- Combining engine and anti-lock brake data to create traction control;
- Use of a single key pad to control the farebox, destination sign, and automatic stop annunciator;
- Combining passenger counters, destination signs, AVL, and other electronic devices to provide detailed information concerning fare and passenger trends;
- Use of a data network and microprocessor to control electrical devices such as lights, horn, etc. (i.e., multiplexing); and
- Exchanging vehicle speed and door position information to activate passenger door interlocks.

The degree to which components can exchange data depends on whether the network is based on standard (i.e., open) or proprietary (i.e., closed) communication protocols. Fully open data networks allow components made by different manufacturers to be used interchangeably on the network (i.e., in a "plug and play" fashion). An analogy would be the personal computer (PC) where keyboards, monitors and software programs from different suppliers can all be used interchangeably. Conversely, fully closed systems are restricted to specific products licensed to use the network. Additional information on data networks is provided in Chapter 5.

Stage 4: Off-Board Integration Improves Monitoring

In the fourth stage of electronic application, data produced from electronic components are transmitted to remote, off-board locations. The transfer can occur through a physical cable connection made to the component or through radio frequency (RF) transmission. RF transmission of data can be done automatically as the bus enters the transit facility or via the radio system.

The transfer of data using radio systems was greatly enhanced with the introduction of automatic vehicle location (AVL) systems. Originally developed to monitor bus location for schedule adherence and security purposes, AVL was expanded to include ridership information by integrating on-board passenger counting devices. In 1979, MTA New York City Transit (NYCT) became the first to transmit real-time information pertaining to passenger utilization and drivetrain performance (8).

The concept of using AVL and radio systems to transmit data back to the transit facility has unlimited potential. Common in aerospace and trucking applications, the technology is becoming increasingly popular in bus transit. Serving as a catalyst for off-board data transmission is the Intelligent Transportation Systems (ITS) program implemented by the Intermodal Surface Transportation Efficiency Act of 1991 (ISTEA) and continued under TEA-21. ITS applies electronic technologies to reduce traffic congestion and make all forms of surface transportation more efficient. Additional information on ITS is provided in Chapter 6.

Stage 5:
"Super Systems" of the Future

In a future fifth stage of development, the integration of high-powered computers will accomplish tasks previously reserved for humans only, adding a new dimension to all forms of transportation. One transit example involved a bus demonstration of an automated road guidance system at Houston Metro (9). The system, which required no electronic signaling from the road itself, used video cameras to keep the bus centered in its lane and at safe distances from other vehicles. If successful, the system could permit a greater number of buses in high occupancy vehicle (HOV) lanes.

Another example of future electronic application involves the use of artificial-intelligence-based "expert systems" to help maintenance personnel diagnose equipment faults. Used in military, aerospace and other transportation sectors on a limited basis, the technology may be applied to bus transit. Serving as a mechanic's "coach," these computer programs help determine equipment failures and guide mechanics through the repair procedure by providing on-line documentation and graphics.

OVERVIEW OF ELECTRONIC BUS COMPONENTS AND SYSTEMS

This chapter provides specific examples of second-stage electronic application where electronic controls are applied to enhance major bus components. The chapter also includes an introduction to the data networks needed to integrate them. A review of electronic fault monitoring and diagnostics is also provided.

SUMMARY

Electronic controls have become an integral part of virtually every major bus component from engines, transmissions and brakes, to radios and destination signs to name a few. The addition of electronic controls provides certain characteristics that all major components share. In general, electronic controls:

- Replace the wiring, connectors, and relays associated with relay-logic with a single electronic control module (ECM).
- The ECM monitors operating conditions and executes commands based on pre-programmed software.
- The software can be reprogrammed to customize functions.
- Self-monitoring characteristics of the ECM identify out-of-parameter conditions, warn the operator as required, place the component in a safe operating condition to prevent damage (i.e., "limp home" mode), and record the fault in memory for future review.

In addition to improving the functionality of individual components, electronic controls can be integrated through data networks. The sharing of data between electronically controlled components allows the vehicle to perform complex functions and operate more efficiently as a result. To simplify on-board integration, the bus has been divided into three distinct levels: (1) drivetrain level, (2) electrical wiring level (i.e., multiplexing), and (3) information level (i.e., AVL, radios, fareboxes, etc.). Each level employs specific data networks to achieve integration.

Electronically controlled components also have the ability to perform self diagnostics and store performance history in memory, allowing maintenance personnel to access the data. Access to diagnostic infomation, typically accomplished on a component-by-component basis, can be consolidated into a single source. Early attempts to centralize on-board diagnostics were made in New York, Michigan, and Canada during the 1980s. Recent developments in electronic technology could help overcome problems associated with earlier systems.

DRIVETRAIN COMPONENTS

Engines

Electronically controlled diesel bus engines were introduced in 1985. Today, every bus is powered by one, and electronic controls have been optimized into smaller designs with more speed, memory, and features. In a typical application, an ECM serves as the engine's command center. It receives signals from the electronic throttle pedal, vehicle speed sensor, turbo boost sensor, air temperature sensor, fluid temperature sensors, oil pressor sensor, and other sensors. Based on this information, a "map" or built-in software program executes commands to control the delivery of fuel into the engine at precise amounts and intervals.

The ECM reacts instantaneously to changing conditions. Matching fuel delivery with specific operating conditions improves overall engine performance and enables the engine to meet stringent EPA exhaust emission regulations. Electronics has made possible several additional features including: automatic engine protection and shut-down; control of cooling fan speed based on temperature; the ability to compensate for normal engine wear; the ability to change engine parameters such as horsepower and top speed; data storage for future review; and the ability to provide diagnostic assistance to facilitate repairs.

The engine's ECM monitors faults by continually comparing inputs with prescribed conditions. When parameters are exceeded a signal can be sent to the operator, the engine can place itself in a protection mode, and diagnostic codes and operating data are stored in memory. Mechanics can access the data using a handheld reading device or PC. Electronic controls also reduce maintenance requirements because adjustments are not required to compensate for the normal wear associated with mechanical actuators. Maintenance personnel, however, do need to acquire a new set of computer skills to operate the diagnostic equiment, and to convert diagnostic codes into repair ation.

Since the engine is integrated with other components, it stores a vast amount of data such as emergency brake applications, excessive idle time, and the engine's speed and load characteristics. Much of this data, however, is available through additional software packages.

Transmissions

The automatic transmission's ECM determines the optimum time at which to change from one gear ratio to another. Electronic signals are sent to the ECM from several devices including the throttle pedal, shift selector, and sensors that measure engine speed and torque, transmission output speed, and vehicle speed. Based on the inputs, the ECM controls the application of internal clutches to optimize shift quality. The ECM can compensate for vehicle weight, engine power, the friction coefficient of clutch discs, and changes in oil temperature and viscosity. It also uses data received from the accelerator and brake pedals to activate the retarder for optimum braking assist.

Electronic transmission controls have improved shift smoothness and consistency, and fuel economy. Similar to electronic-controlled engines, the transmission has built-in protection features and self-monitoring characteristics.

Anti-Lock Brakes

Anti-Lock Brakes (ABS) first appeared in 1975 on buses in response to a Federal Motor Vehicle Safety Standard (FMVSS) requirement. Performance and reliability problems, however, caused the requirement to be repealed in 1978. Since then, advancements in electronic controls have improved ABS. Due to these improvements, ABS is required on all air-braked buses built as of March 1, 1998 intended for use in the United States. Additionally, hydraulically braked buses with a gross vehicle weight rating (GVWR) of 10,000 pounds or more will require ABS as of March 1, 1999.

ABS is an electronic system that monitors and controls wheel speed during braking (10). This controlled action prevents the brakes from locking, enabling the vehicle to stop with improved stability and steering control. ABS also improves tire wear, especially by preventing the "flat spots" that occur when tires remain locked for prolonged distances. The ABS system consists of wheel speed sensing equipment, an ECM, brake pressure modulator valves, and a variety of electrical harnesses, relays, switches, and lamps. Figure 2-1 shows the placement of electronic and pneumatic components in an ABS braking system.

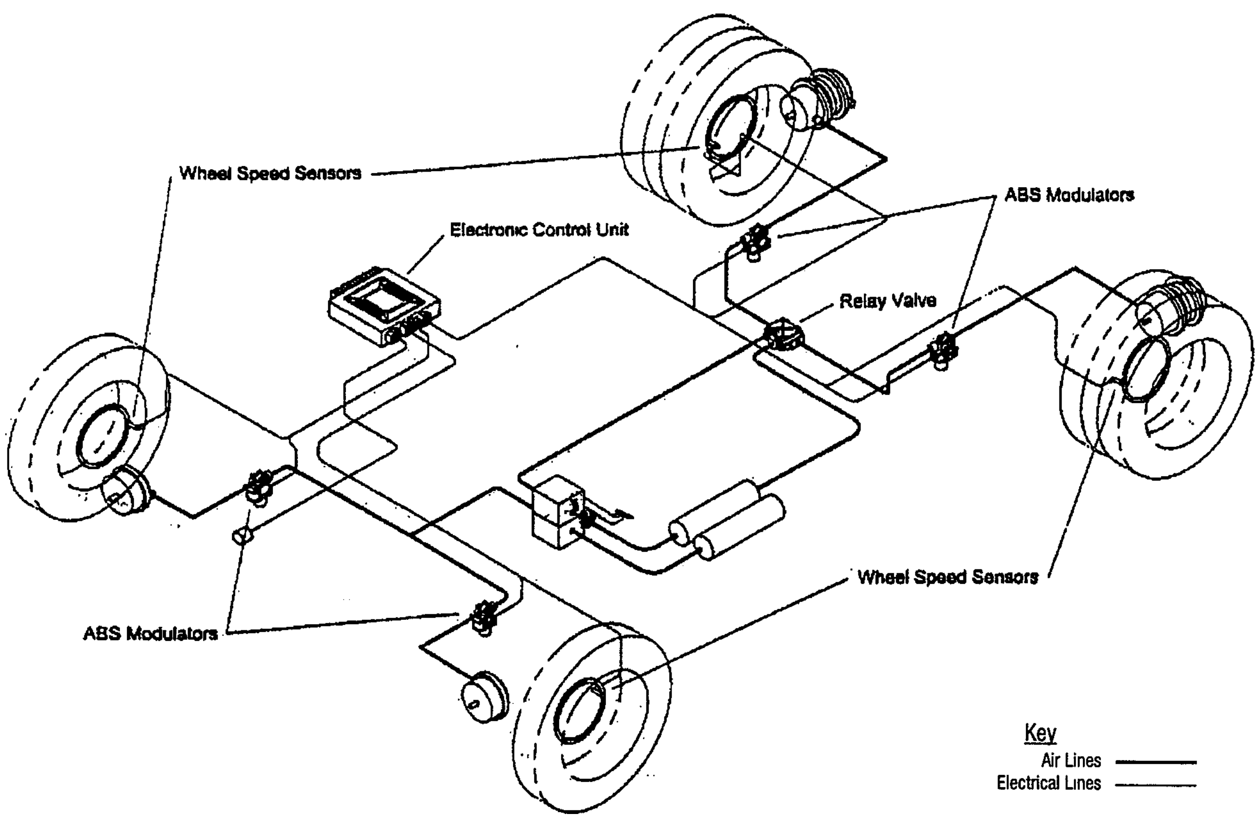

Figure 2-1 ABS component installation diagram. (Courtesy of Meritor WABCO)

Electronic sensors continually monitor wheel speed, sending data to the ECM. When a particular wheel locks, the ECM sends output signals to the locked wheel, momentarily releasing air brake presure. Once the wheel begins to accelerate again, the pressure is reapplied. The process of releasing and applying air pressure occurs at a rate of about five times per second until the wheel speed approaches vehicle speed, and the vehicle finally stops. Modulating air brake pressure at a rapid rate allows the bus to stop safely without locking its wheels or loosing control. The ECM continuously checks itself and indicates any faults to the operator via a dash-mounted warning lamp. Data is also stored in memory for retrieval by maintenance personnel. Using a diagnostic port, mechanics can acess data with product-specific tools or universal tools mated to a special adapter.

ABS systems can also be enhanced with additional components to provide automatic traction control (ATC), also referred to as anti spin regulation (ASR). ATC limits excessive wheel spin during acceleration by applying brake pressure automatically to the spinning wheel regardless of the operator's actions.

BODY AND CHASSIS COMPONENTS

Heating, Ventilation and Air Conditioning (HVAC)

Early HVAC systems consisted of simple switches to control on/off functions in either "heat" or "cool" modes. Electro-magnetic thermostats followed, which opened and closed contacts automatically when predetermined temperatures were obtained. Further enhancements, such as the ability to shut down the HVAC system under a specific set of conditions, added more wires, relays, and complexity to the relay-logic control system. When an automatic shutdown did occur, mechanics had to trace individual wires to determine the fault.

The addition of microprocessor controls has produced several HVAC benefits. Significant amounts of wiring and the number of relays needed to control comfort and safety functions have been reduced. Instead, a single ECM monitors system inputs from one location. Using pre-programmed logic, the ECM responds to specific conditions and initiates a greater range of actions. For example, if the ECM detects a failure in one temperature probe it can switch to another. If compressor cycles are too frequent, the control unit can shut it down to prevent damage and inform the operator with a warning signal. Alarm code histories saved in the ECM's memory can be accessed by service personnel to pinpoint the exact fault.

Other HVAC benefits made possible by electronics include the ability to reprogram software to customize functions, and to accommodate new equipment and features. New developments in sensor technology allow the trucking industry to monitor refrigeration temperatures via satellite. Additionally, tests are underway to permit mechanics to monitor system pressure without connecting gauges.

Integrating the HVAC control unit with other electronically controlled components provides additional benefits. In an optimized system, information such as engine speed, coolant temperature, and alternator status can be exchanged to reduce the need for duplicate sensors and wiring. Likewise, the HVAC's ECM can provide data to control auxiliary heating units and floor-level heaters.

Doors

Compressed air has powered bus doors for over 50 years because it was readily available from the brake system. Furthermore, piping, control valves and troubleshooting were all straightforward. Pneumatic operation existed without much competition because electric motors tended to be expensive and hydraulic systems were prone to leaks.

Recently, however, several factors have combined to challenge the need for pneumatic actuation of bus doors (11):

- Interest in electrically propelled buses including battery, hybrid, and some trolley bus applications using dynamic braking and other technologies that eliminate the need for air brake and pneumatic systems.
- Interest in reducing overall bus weight;
- A decline in the cost of electric motors;
- Development of electronic systems that offer more precise control of door speed, door closing, sealing force, and other functions; and
- A desire by transit agencies to add more door control functions.

Regardless of how a bus door is powered (i.e., electrically or pneumatically), electronics has the potential to provide overall control. Based on signals received from various sensors, the ECM can manage brake and accelerator interlocks, wheelchair lift/ramp systems, stepwell lamps, overhead lights to reduce windshield glare, stop request signals, and other devices. If an out-of-parameter condition exists, the ECM can react in a prescribed manner to trigger alarms, vehicle brakes, and various interlocks to prevent unsafe conditions.

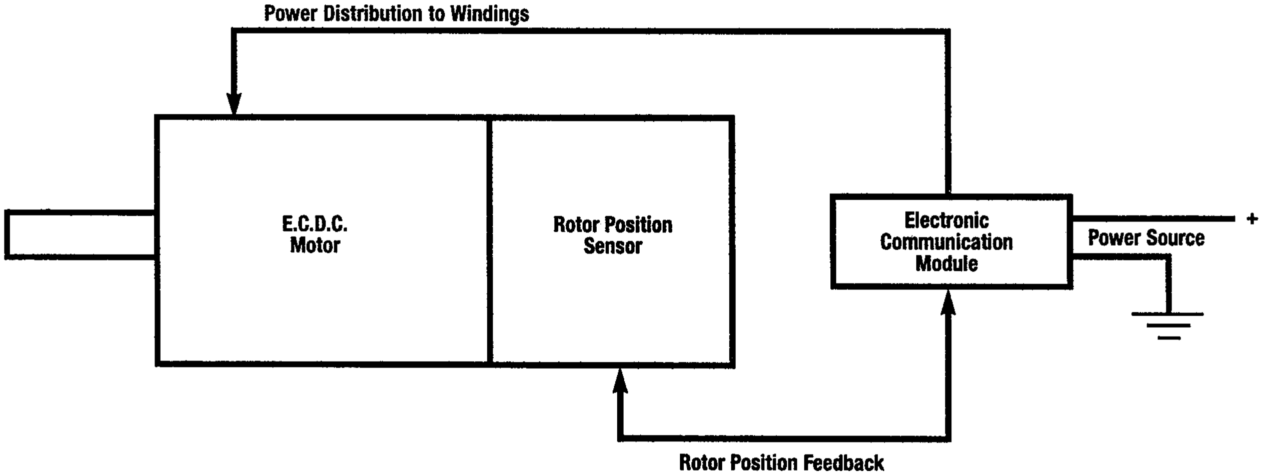

Figure 2-2 ***Block diagram of a brushless motor****. (Courtesy of EG&G Rotron)*

Operating parameters can also be reprogrammed with a laptop computer to suit individual agencies.

If a sensor or subsystem component should fail, the control unit reverts to a safe condition and records the failure in memory. Fault codes displayed on the control unit indicate the failure and direct mechanics to the problem.

Brushless DC Motors

Electronically commutated DC motors, also known as brushless motors, have been in use for over 25 years in military and aerospace applications. During the 1980s, the availability of three technologies have made brushless motors economical for automotive applications (12):

(1) High-efficiency, reliable, and low-cost power transistors, which allow high-current electronic drives to be integral with the motor.

(2) Rare-earth, permanent magnet materials, which allow higher efficiency in a smaller motor design.

(3) The hall effect device, which simplifies the identification of rotor position.

In basic terms, a brushless motor accomplishes the commutation of motor current electronically instead of using brush contacts. The system consists of a permanent magnet synchronous motor, rotor position sensor, and electronic commutation module. The rotor position sensor uses hall effect devices, which provides a digital address for each rotor position. Depending on the position, the hall effect devices activate transistors that switch current through the proper motor windings for maximum torque. As the motor rotates, a new set of windings is energized. Transistors replace the copper commutator and carbon brushes. As a result, there are no wearing components except for bearings. Figure 2-2 shows a block diagram of a brushless motor.

A brushless motor operates in an opposite manner than a brush motor. In a brush motor, permanent magnets are located within the stator (the stationary portion of the motor), while the rotating portion (rotor/armature) consists of a wound copper assembly. In a brushless motor, permanent magnets are contained in the rotor; copper windings are located in the stator.

Brushless motors can be used in a variety of lowvoltage bus applications including HVAC fans, coolant circulating pumps, and electrically driven radiator cooling fans. Potential benefits include:

- Increased service life and reduced maintenance costs due to the elimination of brushes and commutators;
- The ability to limit in-rush currents on initial motor start-up, reducing impact to the power supply system;
- The ability to incorporate variable speed control; and
- Reduced heat because the external stator has a direct path for heat dissipation.

Manufacturers are currently investigating the application of microprocessor controls to brushless motors to provide further benefits. Instead of manually customizing the motor with separate components to add features (i.e., reversibility, multi speeds, adjust timing for soft start ups, etc.), changes could be made through software programming. Additionally, faults such as excessive heat and impending bearing failure could be saved in memory for fault detection.

LED Exterior Lamps

Traditional incandescent light bulbs are composed of a thin filament suspended between electrodes. The filament used to generate the light deteriorates over time, and is prone to premature failure due to road shock and vibration (13). Used extensively for interior warning lamps, recent developments in LED (light-emitting diode) technology have produced enough light to satisfy FMVSS 108 requirements for exterior applications. Examples include identification (ID), clearance, tail, brake, and turn signal lighting.

LEDs reportedly have a life expectancy 50 times that of incandescent bulbs (14). As a solid-state device, LEDs use 98 percent of their power to produce light with only two percent dissipated as heat. As a result, LEDs should not experience the same type of degradation and failure as incandescent lamps. Instead, they experience a gradual reduction in light output over time.

In addition to extended life, LEDs have a faster response time (10 milliseconds versus 200 milliseconds for incandescent lamps) because they do not require heat to generate light. At 30 mph, the faster response rate calculates to about eight additional feet of brake light visibility for a trailing vehicle, helping to reduce rear-end collisions. Other benefits include reduced power demands, greater assurance that lamps will function, reduced in-rush current, and reduced stress on electric contacts.

TELECOMMUNICATIONS SYSTEMS

Radio Systems

Traditional radio systems consist of individual channels assigned to a specific group of users who listen to determine if a channel is free. Although inexpensive and simple to design and maintain, these radio systems cannot make efficient use of idle channels.

In a trunked radio system, a small number of channels are shared by a large number of users and channel selection is controlled by a central computer. When the dispatcher requests communication with a bus, the system automatically switches to an unused channel. The system also switches the called bus to the same channel automatically. There are several standards for trunked systems, without one having supremacy over another. Most radio systems are based on proprietary systems, which lock users into a particular manufacturer's equipment.

Advantages associated with trunked systems include efficient channel utilization, high reliability, and privacy (i.e., operators in other vehicles cannot hear the conversations). While appropriate for voice communication, data channels are not typically trunked because of the time needed to establish the call. Disadvantages with trunked radios include increased complexity and the need for a dedicated control channel.

The vast majority of transit agencies use analog radio communication services for both traditional and trunked systems. A few have upgraded to newer digital systems. In a digital system, the analog voice signal is encoded into a digital format and transmitted over the radio channel. At the transit agency, the digitized voice signal is converted back to its original analog electrical signal and projected over a speaker. Advantages include improved voice quality, greater immunity from noise, privacy from analog scanners, and the ability to accommodate narrower channel bands. Disadvantages include increased complexity and cost.

In addition to voice communication, digital radio permits the transmission of data as part of an integrated system. However, protocols used to support digital applications are proprietary. One such protocol involves a service called cellular digital packet data (CDPD). Similar to E-mail and cellular phones, data can be transmitted between the bus and transit agency by paying a transaction-based user fee.

A growing number of agencies are exploring new applications for transmitting data. They include sending text messages between the bus and central control, and real-time monitoring of bus location and the status of on-board equipment. Because the requirements for data transmission are high, most AVL systems dedicate a separate channel for data transmission. As a result of the increased reliance on radio communications, available frequencies are reaching the point of saturation and will require alternative solutions.

An alternative to radio overcrowding is to become a subordinate user, where permission to operate is made possible by using several frequencies on a non-interfering basis. "Spread spectrum" systems, as they are called, incorporate the use of a unique code that spreads the signal over a broader area of the channel spectrum. Since the signal is generally weaker than the noise threshold, the radio receiver uses the same unique code to recover the signal. By using different codes, many conversations could be supported within the same channel spectrum without interfering with each other.

Other alternatives to radio overcrowding include the use of excess side bands of commercial FM radio stations, and renting commercial radio services.

The Federal Communication Commission (FCC) is working to alleviate frequency spectrum overcrowding by proposing plans to "refarm" or partition existing 25 KHz mobile radio communication bands into narrower channels (15). Equipment needed to operate in narrower channels is 10 to 40 percent more expensive than existing wide-channel equipment, especially when it involves digital technology.

It first appeared that transit agencies would be forced to convert to narrower-bands. Recent provisions, however, allow agencies to use existing systems until their entire radio system is replaced. Despite the exemption, refarming is expected to impact transit. One factor involves the auctioning of certain telecommunication spectrum to the private sector. Although transit spectrum is exempt, auctioning to the "highest bidder" may limit transit attempts to obtain new spectrum at reasonable cost.

As ITS and other factors place increased demands on bus communication systems, agencies should keep informed of developments in spectrum allocation. Particular attention should also be given to new telecommunication alternatives and rapidly developing technologies. According to a study conducted by the FTA, the transit industry needs to have a strong voice in the spectrum allocation area, not only to obtain additional spectrum but to protect what it already has (16).

Automatic Vehicle Location

Automatic Vehicle Location Systems (AVL) are computer-based tracking systems used to identify the location of buses throughout a geographical region in real time. It is based on a geographic information system (GIS), consisting of an electronic map and database that allow a user to visualize and analyze data in relationship to geographic location. For transit applications, GIS would include the underlying basemap that contains the network of municipal streets, highways, and other roads. Specific items such as bus routes, bus stops, park and ride lots, scheduling and timepoints, points of interest and other transit-specific items are then overlaid onto the basemap.

Data requirements for a GIS are extensive and generally require a database management system to manage, store, and access data. Firms that specialize in software applications build programs that merge transitspecific items with the basemap to produce AVL features such as monitoring schedule adherence and transfer points.

Location information from the bus is transmitted back to the agency and displayed on route and street maps using workstations or personal computers. Bus operators can also monitor their performance via an onboard display terminal. Information obtained from the AVL system is often combined with computer-aided dispatch (CAD) software to assist with scheduling.

AVL systems exist in approximately 30 North American agencies, with another 36 either installing or planning to install systems (8). Most of the increase has come since 1990. Expanded use of AVL systems is being driven by the following expected benefits:

- Increased dispatch and operating efficiency;
- Increased ridership due to more reliable and efficient service;
- Faster response to service interruptions and early detection of mechanical problems;
- The ability to provide additional passenger information systems such as automatic stop annunciation, off-board traveler information, etc.;
- Increased driver and passenger security through the use of silent alarms, covert microphones, and on-board surveillance cameras;
- Traffic signal preemption; and
- The ability to collect planning data more accurately than manual sampling methods.

The primary technologies used in current AVL systems consist of a combination of signposts and odometer, and global positioning system (GPS) technology. Until recently, signpost and odometer technology was the most common. It uses a series of radio beacons, typically placed along the route on telephone poles, to send a low power signal with a unique identification code. Buses receive the ID code as they pass by. When polled, they would transmit the most recent signpost ID. Using the odometer, the bus also transmits the mileage traveled since passing the signpost.

AVL systems using signpost/odometer technology have certain drawbacks. Signpost transmitters are prone to vandalism and require periodic battery replacements. Any deviation to the planned route (i.e., road construction) temporarily places the bus out of range. Additionally, route changes require the installation of new signposts.

Agencies that procured their system during the 1980s or early 1990s are the only ones continuing to use signpost technology (8). The clear choice of AVL technology today involves GPS, which uses 24 orbitbased satellites operated by the U.S. Department of Defense, and receivers placed on the roof of each bus. Coverage area includes all of North America.

In earlier systems, buses would send location information when polled from the control center. Information was then compared to a database where route and schedule adherence could be evaluated. Socalled "smart buses" contain a route/schedule data base in the on-board vehicle logic unit (VLU). Since the bus can calculate its own position and determine schedule adherence, it only reports to central control when running outside the predefined schedule limits. As a result, a separate polling data channel is not required. Additionally, the reduced need for data transfer allows more buses to share the same data channel.

GPS signals can be degraded when vehicles are positioned between tall buildings and dense foliage, or when traveling underground. Another impediment to accuracy involves Selective Availability (SA), which is present on all commercial GPS receivers. SA is a technique used to intentionally degrade the accuracy of commercial GPS receivers to protect U.S. military interests in times of crisis. With SA enabled GPS's accuracy is only about 300 feet (91 meters), compared to 50 feet (15 meters) when SA is not operating. Other factors contributing to the inaccuracy of GPS include satellite and receiver errors, and atmospheric conditions.

As a result of the conditions described above, GPS typically requires additional technologies to help improve location accuracy. One method involves the use of Differential GPS (DGPS). In simple terms, DGPS uses a fixed receiver mounted in a known location to confirm the accuracy of GPS signaling. If the location of a known structure as reported by GPS differs from the actual location, the differential or "correction factor" is applied to improve the accuracy of bus location. The correction factor can be based on a transit agency maintaining its own fixed site, through U.S. Coast Guard maintained DGPS sites, or from companies that transmit differential correction data using FM radio frequencies. However, if the GPS signal is blocked, differential GPS is of no benefit.

Another method to improve the accuracy of GPS when satellites become obstructed involves the use of an odometer, which calculates position based on the distance traveled since the last signal was received. Signposts are also used in specific locations to supplement GPS in areas of poor reception.

Dead Reckoning is a technique that can be used as a stand-alone method of determining vehicle location or to supplement an existing GPS system. It measures the vehicle's acceleration and direction. Using a known starting point as a reference, the dead reckoning unit uses odometer and compass inputs to determine vehicle position from the starting point. Fiber optic gyroscopes can also be used to assist the dead reckoning process.

If dead reckoning is used as a stand-alone system, there must be an external way of periodically "registering" the vehicle at certain locations. This can be accomplished through signposts, or by requiring the operator to make a manual input at selected bus stops.

AUTOMATIC PASSENGER COUNTERS

First used in the 1970s, automatic passenger counters (APC) record passenger boardings using different technologies. Mechanical systems react to the pressure of a passenger's foot as he/she steps on a treadle mat; electronic systems use infrared light beams. As a passenger boards or leaves the bus, two infrared beams placed across the passenger's path are broken in a particular sequence to register the activity.

To link passenger activity with specific route stops, APC systems are also used in conjunction with AVL systems. APC can also be installed as a stand-alone system using any one of the vehicle-positioning options mentioned above. Transmitting APC data depends on how quickly an agency plans to use the data. The two most common options include real-time (at least once every 10 seconds) and off-line (delayed).

If real-time data is required for dispatching purposes, the APC unit must be integrated with the AVL and radio systems. Agencies, however, need to consider the cost of fitting each bus with APC equipment and the extra radio capacity required to transmit the data in real time.

A more cost-effective alternative is to rotate a limited number of APC-equipped buses periodically on all routes. Using this approach, passenger counting data could be downloaded using several methods: a physical plug-in cable connection made between the APC and a laptop computer; a short-distance radio frequency (RF) link established between the APC and the bus; or a disk taken from the APC to a computer.

ON-BOARD PASSENGER INFORMATION

As one of its provisions, the Americans with Disabilities Act (ADA) requires buses over 22 feet in length to have a system that announces route stops and provides other passenger information (17). To satisfy these requirements, some agencies use electronic systems that automatically trigger voice announcements using pre-recorded messages. Complementing the audio system are interior signs for the hearing impaired.

The method used to trigger information depends on whether the agency has an AVL system. Agencies with AVL typically integrate in-vehicle passenger information systems with existing location technology to trigger announcements. Using GPS signals, the control unit automatically determines adherence to the bus route and triggers next-stop information. The system can also detect when a bus goes off route and remains silent. When back on route the system picks up where it left off, announcing the next scheduled stop without driver intervention.

Agencies without AVL can apply next-stop announcement systems in one of two ways. In a manually-triggered approach, the operator depresses a key pad button or foot switch to activate the interior destination sign and/or pre-recorded voice announcement. Another approach is to specify GPS as a stand-alone triggering system for announcements. The stand-alone system could be expanded at a later date into a full AVL system.

FARE PAYMENT SYSTEMS

Background

Fare payment technology has come a long way from the mechanical "drop box." As fares approached one dollar in the late 1970s, agencies turned to electronic registering fareboxes to process cash, tickets and tokens; and to record trip-related data such as zone and passenger type. The first electronic fareboxes were troublesome due to poor design and lack of electronically skilled maintenance personnel. Today, reliability has improved and electronics has expanded the role of fare collection to include several new technologies (18, 19, 20).

The application of electronics has the potential of offering agencies a variety of fare objectives which may include:

- A pricing structure based on distance traveled, time of day, and type of passenger;
- The reduction and eventual elimination of cash fares to improve security and lower handling costs;
- Automation of the settlement process with financial institutions (i.e., banks) to lower costs; and
- The creation of multi-modal networks that are seamless to the passenger, but operationally and organizationally sound for the agencies involved.

This review focuses on electronic developments in two areas: fare media such as magnetic tickets and smart cards; and fareboxes that process the media.

Non-Cash Fare Media

Although cash is the most common means of paying fares, agencies are investigating non-cash media to circumvent cost and security issues associated with handling cash. Non-cash media include a type of ticket or card that contains printed information and/or stored information. Paper tickets typically include printed information only, while magnetic tickets and smart cards use electronic technology to store information. Potential advantages offered by electronic media include:

- A higher degree of revenue control;
- Increased information pertaining to ridership usage and patterns;
- Increased flexibility in establishing fare options and levels; and
- Regional fare integration that allows riders from different systems to use a single ticket while retaining their individual fare structures.

A major drawback involves the cost of the media and the fare collection equipment needed to process it. Other potential drawbacks include forgery of tickets and the potential for system integration problems that can occur when trying to apply electronic media to a variety of fare collection equipment.

Magnetic Tickets

Magnetic-stripe tickets can be used for a variety of payment options including single-ride, multi-ride, period pass, or stored value. They can be used in buses when the farebox is equipped with ticket readers and processing units. If an agency uses magnetic tickets for its rail system, magnetic-ticket readers in buses allow passengers to use the same fare media. Less than 10 percent of bus systems use magnetic on-board fare collection technology (19).

Smart Cards

Popular in Europe, smart cards are also attracting attention in the U.S. A smart card is a credit-card-size integrated circuit (IC) with built-in logic capabilities. The term is also used to describe "memory cards" that store information but do not contain internal processors. Smart cards store large amounts of data, offer increased security, and have a longer life cycle compared to magnetic-stripe cards. They can also maintain different accounts within their memory for different clients or agencies (i.e., bank and department store transactions), and are easy to add value to. Smart cards typically fall into two categories:

1) Contact Cards that require a physical contact between the card and reading device; and
2) Proximity Cards that transfer data without making physical contact with the reader.

Fareboxes

Electronically registering fareboxes are commonplace in buses today. In a typical scenario, the operator uses a keypad to indicate a fare category for a boarding passenger, and to enter identifiers such as operator ID and route number. As each passenger boards, information is captured regarding the fare category, payment media and the amount of cash received. Improved security measures include electronic tracking of revenue and data as the cashbox and vault are moved throughout the property.

Technology developments include the fitting of swipe readers to accept magnetic tickets, and ticket processing units (TPUs). TPUs issue paper transfers, or issue and accept magnetically encoded tickets. Tickets obtained from a vending machine, or the TPU of another bus, are processed onboard by deducting value or a ride. A display informs passengers of the remaining value/rides.

Another major development involves the use of transactional databases. In a traditional summary database, information from each transaction is not saved but is used to update cumulative records (i.e., number of boardings in each fare category, fare revenue, etc.). The summation continues until the operator enters a change (i.e., route, direction, run or change of operator). Transactional data offers greater flexibility because a record is created and stored for each transaction including the fare category, payment media, operator route, and run number. A time stamp is also included with each transaction.

The detailed accounting of each transaction allows agencies to obtain more meaningful statistics including the tracking of promotional based fares, fare media issued by other agencies for revenue allocation purposes, and linked-trip patterns (21).

The next stage of farebox development involves integration with other on-board electronic equipment such as AVL, passenger counters, destination signs, and others. For example, if transactional records were also stamped with the vehicle location, passenger boardings and related fare data could be segmented by each stop. Integration with other devices also permits the use of a single keypad to reduce the need for redundant hardware and multiple sign-ons by the operator. Integration of the various components requires them to be compatible with one another, which may be difficult if procured independently at different times.

ELECTRICAL MULTIPLEXING/DATA NETWORKS

Multiplexing is a term used to describe a broad range of procedures that involve the integration of electronic components and systems. In simple terms, multiplexing can be described as a way of transmitting several lines of communication simultaneously on the same network (22). The telephone system serves as a good analogy. Although telephones are all connected through a worldwide network, the network is accomplished by sharing communication lines — not by running separate wires to every possible combination of phones.

As the transit bus developed since the 1970s, two issues needed to be addressed:

(1) The growing number of devices requiring battery power increased the size and complexity of the relay-logic-based control system; and
(2) Electronically controlled components with the ability to exchange data required a method to "communicate" with one another.

Electrical system multiplexing was applied to buses as a way of streamlining the electrical system. Data networks, developed by the Society of Automotive Engineers (SAE), were applied to integrate electronically controlled components. First applied to the integration of drivetrain components, SAE data networks were expanded to include other equipment as well.

Electrical System Multiplexing

To resolve the problem of using individual point-to-point wires and relays to control each component, bus manufacturers have replaced traditional wiring systems with electrical system multiplexing. In a "multiplexed" system, a microprocessor uses software and its own twoway data network to control power switching to electrical devices. Instead of running separate power and ground wires throughout the bus, data signals are sent to modules located at strategic locations. The localized modules, which contain battery power and ground, distribute electrical current as directed by the system's microprocessor. Controlling the switching of power from specific locations generates savings in space, weight, design time, installation, troubleshooting, and general maintenance (23). Detailed information on electrical system multiplexing is provided in Chapter 4.

Data Networks

To address the transfer of data between electronically controlled components in heavy-duty vehicles, SAE developed serial data communication standards. The process of data transfer is identified by many names. Some of the more common terms include: data networks, data link, data bus, or simply bus. To avoid confusion with transit "bus," this study will use "data network" to denote the exchange of data between electronic components and systems.

A data network uses a process by which information generated by one device is converted from parallel form to serial form so it can be transported to another device. Once received, the information is converted back to parallel form. The purpose of converting information is to reduce the hardware and costs associated with connectors and cables.

Data networks ensure that all devices connected to it interpret data in the same manner. One example is vehicle speed, an important piece of information that can be used by a number of components. However, before a single speed sensor can provide identical information to all components, the format of that information must be specified. Data networks are merely the specifications used to define how information is transferred from one device to another. Additional information on data networks is provided in Chapter 5.

The Three Levels of Data Networks

A popular misconception concerning electronic integration is that a "universal" system is used to exchange data throughout the bus from engines, transmissions, and anti-lock brakes, to AVL, destination signs, fareboxes, and the wiring system itself. While this is a lofty goal and may someday be the case, the use of a single data network does not exist in bus applications for one primary reason. While electronic bus systems were developing, there was no single network with the capability of handling data interactions between all electronic components. Hence, separate data networks were applied to specific bus systems as they developed.

To simplify our explanation, the application of data networks is organized in three bus levels to reflect the development process. This three-tier segmentation is consistent with the development approach being pursued in both the U.S. and Europe. Although different terms are used to identify the three levels, this study will refer to them as the Drivetrain Level, Electrical Level, and Information Level. Figure 2-3 shows each of the three levels superimposed on a bus.

It is important to note that Drivetrain and Electrical Level integration is accomplished by the bus manufacturer and delivered to the transit agency as a complete operating system. Information Level integration, however, is typically accomplished by system integrators who tend to install equipment after the bus has been assembled.

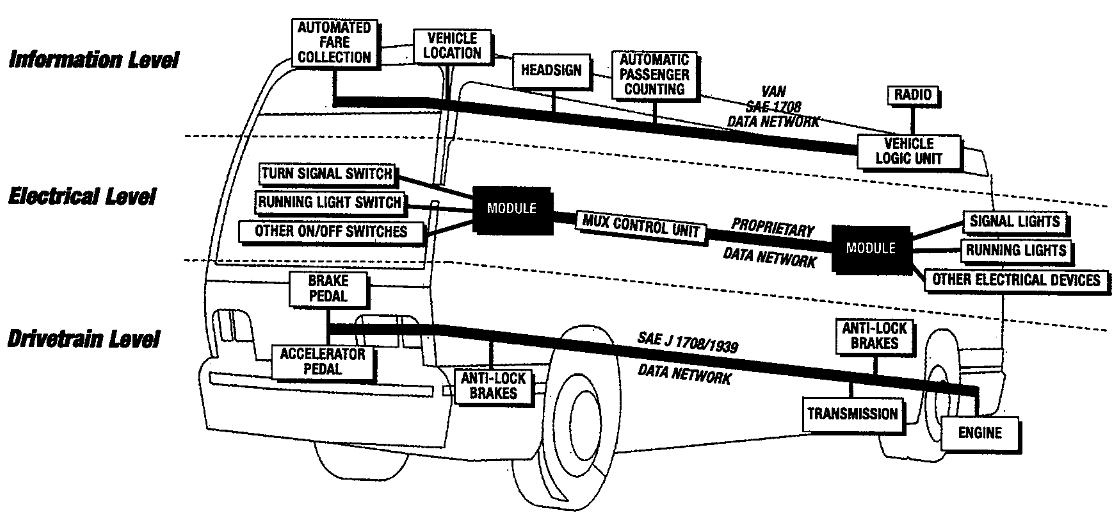

Figure 2-3 The three levels of electronic integration developed around separate data networks.

Drivetrain Level **-** This level includes components critical to vehicle driveability such as the engine, transmission, retarder, anti-lock brakes (ABS), and traction control systems. Due to their critical nature, bus manufacturers apply data networks developed by SAE exclusively for drivetrain components. The use of dedicated networks prevents critical drivetrain-related components from being impacted by other bus functions.

Electrical Level **-** This level represents the electrical system of the bus that controls power throughout the vehicle. In a traditional system, individual wires provide power and ground to control electrical devices through a series of relays, known as relay logic. To overcome this complexity, virtually every transit bus manufactured today offers a streamlined wiring system that many generically refer to as "multiplexing."

Multiplex electrical systems are typically used to control relatively simple 12- and 24-volt functions. Examples include turning electrical devices on/off, serving as a signal/emergency flasher, and initiating time delays.

Information Level **-** Components and systems in this level include AVL, destination signs, fare collection, automatic annunciators, camera security, APC, and other components. This area of the bus is receiving particular attention because of its ability to furnish information needed to provide a higher level of service efficiency to passengers. In the U.S., efforts to integrate components in this level center around the "Vehicle Area Network" or VAN.

Integration at this level can range from combining a few basic functions to consolidating virtually every on-board device. Combining of functions at this level is typically carried out by system integrators, companies that specialize in AVL and communication technologies. At the heart of the system is a vehicle logic unit (VLU) integrated with the radio. As a microprocessor, the VLU has the ability to monitor all activity on the network, store data for future retrieval, or transmit data to the agency for real-time monitoring.

VAN has adopted the SAE J1708 data network as the foundation for this level, while the Europeans are generally using the Controller Area Network (CAN) developed by Bosch. (France is proposing a separate, WorldFIP protocol). Each network provides a standard "language" that electronic components can use to "communicate" with one another. Without it, the integration of electronic components would not be possible.

Gateways Combine Data Networks

Although the bus has been divided into three levels for the purpose of explaining electronic integration, the levels are not autonomous. Electronic modules, called "gateways", allow interaction between components operating on different data networks. For example, data from the Drivetrain Level can be sent to the Information Level AVL system to report critical engine malfunctions.

ON-BOARD FAULT MONITORING AND DIAGNOSTICS

As noted earlier, microcontrollers (i.e., ECMs) found in each major component also have the ability to perform self-diagnostic tests. The ability to perform these tests, record the results in memory, and communicate data depends on the capabilities of each component. Drivetrain components typically have the most advanced diagnostic capabilities. Depending on the fault, a drivetrain component can alert the operator and make certain information available to the other drivetrain components. According to instructions built into each component's software program, actions are taken to protect against damage. Depending on the fault, the engine may limit bus speed or shut itself down; the transmission may restrict itself to certain gear ranges.

Fault information can be communicated to maintenance personnel in several ways depending on the component. Those with less critical functions tend to use LED lamps that flash in a particular sequence to indicate faults. In other basic systems, fault codes are displayed directly on the control unit itself. More advanced components, such as those found in the Drivetrain and Information Levels, have greater data storage and diagnostic capabilities. In addition to triggering a warning signal or alarm, the historical data stored within them allows properly trained mechanics to perform a more detailed analysis. The analysis could be in response to a specific warning alarm, or as a review of all operating conditions to identify impending failures.

To access data for further analysis, mechanics use a hand-held reading device or PC. Components such as engines, transmissions, ABS, air conditioning, and other systems have dedicated ports or plug connectors that mate with specific diagnostic tools. The engine and transmission also have plug connectors in the operator's area to perform driveability tests. Although the plug connectors have been standardized in some applications, each product generally requires its own diagnostic tool to extract data. This component-by-

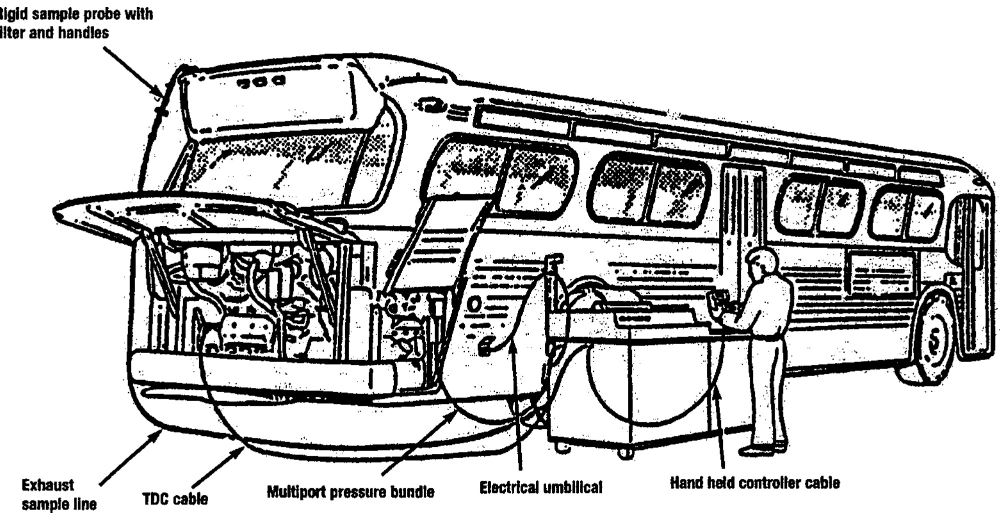

Figure 2-4 Technician performing a scheduled maintenance inspection with assistance from the ABDS Maintenance Area Unit.

component approach to diagnosing faults is the most common method used in bus transit today.

An alternative method involves collecting performance data from several components/systems and directing it to one on-board location for dissemination. Systems integrators, AVL suppliers, and suppliers of electronic data recorders are typically involved in the process of consolidating vehicle performance data. The systems collect and store data by interfacing with existing data links or using separate sensors.

Data are typically stored in an on-board computer or the VLU. Once stored, they can be downloaded for further evaluation, transmitted to radio frequency (RF) transceivers on the service lane, or sent to central maintenance via the radio/AVL system in real-time. Typically monitored conditions include engine oil pressure, engine coolant temperature, air brake pressure and other conditions desired by the agency.

The process to develop a centralized on-board performance monitoring and diagnostic system has been undertaken on an agency-by-agency basis for several years. While some have made substantial progress, the bus industry as a whole has not adopted a universal approach to on-board diagnostics. Doing so will require a coordinated effort by transit agencies, component suppliers, and bus manufacturers.

ABDS

The first known organized attempt to centralize on-board diagnostic functions began in the 1980s when the Federal Transit Administration (then called the Urban Mass Transportation Administration) funded demonstrations of the Automated Bus Diagnostic System (ABDS) in New York City, Syracuse, (NY) and Flint (MI). ABDS was intended to reduce maintenance costs and road calls by providing a means of early fault detection and computer assisted diagnosis (24).

ABDS was comprised of On-Board Bus Sensors, a Fuel Island Unit, and a Maintenance Area Unit. On-Board Sensors collected data from several locations to a single microprocessor. A small door located behind the rear wheelhousing provided access to a plug connector, allowing the bus to communicate with the Fuel Island Unit and the Maintenance Area Unit. The Fuel Island Unit performed daily checks in the service lane, while the Maintenance Area Unit performed more extensive tests during scheduled service intervals. Mechanics were guided through the procedure with a hand-held controller, and provided with a complete post-test report. Figure 2-4 shows the ABDS diagnostic system being used during a scheduled service inspection.

ABDS was developed and tested for nearly ten years until funding and manufacturer support eventually ended. Sensors tended to be unreliable, triggering false alarms. Despite the technical problems and lack of support, the MTA in Flint Michigan continued to operate the ABDS system on a limited basis with favorable results (25). FTA's ABDS program was clearly ahead of its time. The self-diagnostic capabilities of today's electronic components combined with data networks could make a similar program useful to bus maintenance.

1988 Canadian On-Board Diagnostic Study

In 1988, a study concerning on-board diagnostics was sponsored by Transport Canada, the Transportation Development Center (TDC), and the Ontario Ministry of Ontario (26). Over 10 years old now, the study recommended an approach that could be applied today, especially with the development of more sophisticated on-board data recorders. The Canadian study recommended a personal computer-based diagnostic system that would:

- Use the capabilities of existing on-board electronics found in engines and transmissions;
- Use data communication protocols developed by the American Trucking Association (ATA) and SAE;
- Be expandable to include other subsystem diagnostics when available; and
- Incorporate expert type assistance in isolating faults.

The study emphasized that transportation electronics will be heavily dependent on software development and urged government officials to cooperate and support these technologies.

CHAPTER 3

ELECTRONIC DEVELOPMENTS IN OTHER TRANSPORTATION SECTORS

Before moving on to describe the use of multiplexing and data networks in buses, this chapter reviews the application of on-board electronics to automobiles, heavy-duty trucks, and rail transit.

SUMMARY

Transit buses are one of the many modes of surface transportation applying on-board electronics to improve safety and operating efficiency. As the largest transportation sector, the automobile plays a leading role. More closely related is the heavy-duty truck, from which buses derive many of their components. An obvious difference between transit buses and their siblings is that automobile and truck manufacturers are more actively involved with the integration of Information Level components.

For example, heavy-duty trucks are delivered to fleets with vehicle location, radio, radar collision avoidance and other systems pre-engineered into the truck. With transit buses, Information Level integration is typically performed as retrofits by systems integrators. Another major difference is that auto and trucking industries have standardized data networks to facilitate the integration, while efforts to do the same by bus transit are still ongoing.

In addition to the many electronic features pertaining to safety and comfort, all new cars and light trucks feature a standardized on-board diagnostic system to detect emissions-related faults. The requirement, based on SAE data networks, allows vehicles built by multiple automakers to be diagnosed at any repair facility using standard tools and procedures.

Operated as independent companies in a highly competitive market, the heavy-duty trucking industry has a long-standing tradition of using electronic technology. Monitoring both the operator and vehicle is essential to maximizing efficiency and profits. Like the auto industry, heavy-duty trucking has developed a universal environment for integrating on-board electronics around standard SAE data networks. The effort was organized by the American Trucking Association (ATA) working in close cooperation with the SAE, suppliers, and fleet operators. Early efforts focused on electronic drivetrain integration, which quickly expanded to include Information Level components. The development of SAE J1708 and J1939 was a result of the collaborative effort to integrate heavy-duty truck electronics.

Trucking companies can choose from a variety of Information Level electronics. Included are global positioning technology and radio communication systems to monitor several vehicle and operator conditions such as excessive idle time, excessive vehicle and engine speed, and cargo refrigeration temperatures. The systems are also used to track and schedule the movement of freight as it travels throughout the country. Each major component is compatible with SAE data networks, allowing fleet operators to choose products from several vendors.

Like its bus counterpart, rail transit is beginning to address the interfacing needs of on-board electronic technology. To fulfil the rail transit industry's desire to contain costs, the Transit Cooperative Research Program (TCRP) is engaged in research that seeks to develop standard interfaces between rail systems and subsystems. An Institute of Electrical and Electronic Engineers (IEEE) Committee is working to develop electronic interface standards in specific areas such as train monitoring, diagnostics, communication protocols, environmental conditions for electronic equipment, and passenger information systems.

AUTOMOBILES

Background

With an annual North American production of over 15 million units, the automobile is clearly the on-highway leader in applying advanced electronics. Due in large part to electronics, today's automobile requires less maintenance, is more reliable, and lasts longer than those built 20 years ago. Electronic ignitions, introduced during the 1970s, represented the first high-volume electronic application followed by electronic fuel injection, cruise control, and intermittent wipers. In the 1980s, electronic advancements included full powertrain control, ABS, traction control, seat memory, crash sensors, remote keyless entry, and other features. During the 1990s, multiplexing, on-board diagnostic systems, navigation systems, and integrated controls were introduced (27).

Analysts project that the automotive electronics market will reach $80 billion worldwide by 2003, more than double the worldwide total of $37 billion in 1993. By 2005, electronic components will equal 20 percent of a vehicle's value, a 5 percent increase from 1996 costs.

Standardized On-Board Diagnostics

The vast majority of automobile electronics enhances passenger comfort, convenience, and safety. An interesting aspect, however, involves the universal application of on-board diagnostics to detect emissions-related faults. Beginning with the 1994 model year, all cars and light trucks are required to have such a system. The requirement stems from a cooperative effort between the Society of Automotive Engineers (SAE), the EPA, and the California Air Resources Board (CARB) (28).

In 1988, CARB required that all cars and light trucks sold in California be equipped with an on-board diagnostic (OBD) system. It provided drivers with an early warning of deteriorating emissions characteristics, and mechanics with basic diagnostic information to correct the problem. Simultaneously, SAE adopted a "Vision of the Future" to address automaker and repair industry concerns over the increasingly complex nature of vehicle electronics. This vision, which remains virtually unchanged today, consists of the following (28):

- All vehicles will use a standard set of diagnostic test modes that can be executed over a standard communication data network;
- A standard connector in a standard location will be fitted to all vehicles;
- Diagnostic tools will be able to extract a minimum set of standardized diagnostic test modes and test information from all vehicles; and
- A system will be in place to allow standard electronic access of all electrical/electronic diagnostic service information.

SAE's vision produced a series of recommended practices to provide the uniformity needed to apply diagnostics across a broad range of manufacturers and vehicles.

Using SAE's recommended practices as a framework, CARB and EPA concurrently issued new onboard diagnostic requirements, known as OBD-II, for 1994 and later model year light and medium duty vehicles (29, 30). Under these regulations, vehicle manufacturers must provide diagnostic information using standardized terminology, fault codes and plug connectors.

Table 3-1 lists the SAE recommended practices mandated by EPA and CARB regulations. The Table also lists the recommended practices that the auto industry has adopted as voluntary in an effort to achieve greater commonality.

	Mandated	**Voluntary**
On-Board	J1850 Communication Protocol J1962 Diagnostic Connector J1979 Diagnostic Test Modes J2012 Diagnostic Trouble Codes	J2178 Class B Non- Diagnostic Messages J2186 Tamper Resistance (CARB) J2190 Enhanced Test Modes J1699 J1850 Verification
Off-Board	J1930 Terms and Definitions J1978 Diagnostic Scan Tool J2205 Expanded Scan Tool Protocol	J2201 Scan Tool Interface J2008 Service Info

Table 3-1 Mandated and voluntary SAE practices for on-board diagnostics applicable to passenger automobiles and light trucks.

Data Networks

For the most part, American automakers have settled on SAE J1850 as the data network for mandated OBD-II diagnostics and all electronic interfacing needs including non-emissions related diagnostics and component integration. However, each of the Big 3 automakers (GM, Ford, and Chrysler) along with European and Japanese automakers, use their own variation of the J1850 network to satisfy proprietary needs. As a result, electronic component suppliers must modify each product to accommodate each of the J1850 variants.

In Europe, automakers have typically settled on the Controller Area Network (CAN) developed and licensed by Bosch. Because of standardization to CAN, European automakers run a separate J1850 data network to satisfy OBD-II requirements for U.S.-marketed vehicles.

Future Developments

Future automotive electronic developments focus on ITS-related functions such as distance-sensitive cruise control, lane departure warning, and fully automated hands-free driving. Distance-sensitive cruise control monitors the distance of vehicles ahead and automatically adjusts the car's speed to maintain a safe gap. Lane departure warning systems respond to driver fatigue by activating a warning buzzer if a car begins to drift out of its established lane. The system can also warn the driver when making an intentional lane change if other vehicles are in the driver's "blind spot."

Fully automated hands-free driving, although a long way from being perfected, has been demonstrated. It requires several technologies including magnetic markers imbedded into highway lanes, on-board lateral and longitudinal control, obstacle detection and avoidance, collision and lane-departure warning, and vehicle-to-vehicle communication. The electronics would allow vehicles to ride on invisible tracks made by magnetic markers imbedded into the pavement. Another approach consists of vision-based systems that use on-board cameras to detect obstacles ahead and to follow painted lane markings.

HEAVY-DUTY TRUCKS

Background

Production of Class 8 heavy-duty trucks in the U.S. and Canada totals about 200,000 units annually, considerably more than the annual production of about 3,000 units for standard-size transit buses. The trucking industry has a long-standing tradition of using electronic technology to monitor both operator and vehicle performance. Electronic journey recorders called "tachographs" were first used to record vehicle movements in speed, time, and distance traveled.

As a deregulated commercial enterprize, the trucking industry is very competitive and overall cost of operation is essential to financial success. Because of this, on-board electronic systems are viewed as a way to operate more efficiently and maximize profits.

On-Board Electronic Integration

All major on-board truck components — engine, transmission, anti-lock brakes, radio communication, vehicle location, data recorder computer, air conditioning, air suspension, dashboard, and radar collision avoidance — are integrated by standard SAE data networks. Integration around these networks provides manufacturers with a level of standardization, keeping them from redesigning each truck to satisfy customer requirements for unique combinations of components.

Development of a universal environment for on-board integration was made possible by the Truck Maintenance Council (TMC) of the American Trucking Association (ATA) working in close cooperation with the SAE. Data networks such as J1708/J1587 and J1939, first developed for both truck and bus drivetrain applications, was a direct result of efforts taken by the ATA and SAE. Further work resulted in standards for a common on-board diagnostic plug connector and diagnostic tool requirements.

Integrated on the network is a data recorder, a microprocessor device similar to the VLU used in transit. It records several vehicle and driver functions including engine speed, vehicle speed, oil pressure, coolant temperature, and refrigeration temperatures. Depending on the application, conditions are stored for review at a later date or sent in real time to a trucking facility.

Additional features include monitoring of the truck's geographical position (i.e., AVL), allowing customers to be informed of freight locations. Geographical positioning also permits trucking companies to match trucks in the field with new freight business. According to one source, about 15,000 trucks have the ability to monitor location and other operating conditions in real time (31). In one case where a truck was stolen, the on-board computer recognized that the operator had not logged on and the vehicle was off its scheduled route. It then used its radio system to notify the police, reporting the truck's exact location to help apprehend the thief (32).

On-board data collection and storage systems for trucks also have provisions that allow the operator to enter additional information such as fuel purchases and other expenses manually. Again, all on-board electronic devices are integrated through common SAE data network. This allows fleet customers to specify components from several manufacturers knowing they will operate on the same network.

A typical new heavy-duty truck incorporates a SAE J1708/J1587 network for Information Level integration, and a J1939 network for Drivetrain Level integration. The trucking industry is working to use either SAE J1708 or the J1939 data network to control on/off type power (i.e., multiplexing) throughout the vehicle.

On-Board Diagnostics

The trucking industry, primarily through the efforts of the TMC, has made substantial progress incorporating on-board diagnostics as part of its overall electronic integration process. The first generation of diagnostics is included in the SAE J1708/1587 protocol, which defines the (33):

- Source of the fault (e.g., engine);
- Failure mode (e.g., open electrical circuit);
- Least repairable component (e.g., the engine oil pressure circuit); and
- Number of times the fault had occurred.

The next generation of on-board diagnostics, as defined by SAE J1939, allows for additional failure modes (up to 32), and least-repairable component identifications (about 500,000).

Bus transit makes use of the same procedures developed by the SAE and TMC to access on-board diagnostic data. The extent to which the data are utilized depends on the capabilities of each agency. According to one authority on vehicle-based electronics, transit lags behind trucking in its ability to make use of the diagnostic data available through existing electronic components (34).

RAIL TRANSIT

Background

Similar to its bus counterpart, rail transit is in a state of transition as it begins to incorporate new onboard electronic technology and address the interfacing needs of this new technology. The first major production of advanced technology heavy rail cars went into service on Boston's Red Line in 1994 (35). Three-phase AC traction motors use microprocessor controls for both propulsion and regenerative braking. Conventional air brakes also incorporate microprocessors to take full advantage of regenerative braking.

Boston's Red Line cars include a comprehensive on-board diagnostic system that can be monitored from a screen at each cab and stored in memory for downloading to a portable computer. Propulsion and braking system diagnostics include a menu-driven software package that allows mechanics to identify a failure based on the lowest replaceable unit level. HVAC and door systems are also microprocessor controlled and linked to the on-board monitoring system.

Future applications of advanced electronics include state-of-the-art rail cars under development for MTA New York City Transit (NYCT). The first deliv-eries of NYCT's "R-142" stainless steel rail cars is expected to begin in the summer of 1999. Advanced on-board electronic features will include microprocessor-controlled regenerative braking, communications-based train controls, trainline multiplexing, a central diagnostic system, digital communication system, and electronic signs and next-stop announcements for passengers (36). Amtrak's high speed cars planned for the Northeast Corridor will also represent state-of-the-art applications of on-board electronics.

Standards Being Developed

Rail transit has recognized that a lack of standardization regarding the application of new technology can contribute to increased costs for rolling stock and spare parts needed to support unique fleets. To help fulfil the rail transit industry's goal of developing standard specifications for new railcars, the TCRP is engaged in research (Project G-4) that uses a formal consensus building approach to develop these standards (37). The standards development process is focusing on the interfaces between specific systems and subsystems, and not the systems and subsystems themselves.

Through TCRP Project G-4, an Institute of Electrical and Electronic Engineers (IEEE) Rail Transit Vehicle Interface Standards Committee has been formed to develop various standards. The IEEE committee has formed individual working groups to develop interface standards in eleven areas:

(1) Communications based train control;
(2) Rail vehicle monitoring and diagnostic systems;
(3) Communication protocols aboard trains;
(4) Environmental conditions for electronic equipment;
(5) Safety considerations for software;
(6) Functioning of interfaces among propulsion, friction brake, and train-borne master control;
(7) Passenger train auxiliary power systems;
(8) Passenger information systems;
(9) Transit Communication Interface Profiles (TCIP) for rail transit;
(10) Rail transit vehicle battery physical interface; and
(11) Motor Control Standards.

The working groups are in the process of developing standards for each area identified. A summary of key activities is provided below.

Communication Protocols

Rail cars are manufactured using pre-assembled modules that perform many different functions. Data networks allow these modules to communicate with one another for purposes such as traction control, diagnostics, and passenger information.

The rail industry does not have a preferred communication standard, allowing train builders to use their own communication approaches. The goal of this working group is to specify the protocols for both inter-car and intra-car data communications. The protocols will permit a variety of suppliers performing different on-board functions to share a common communication method.

According to the TCRP project, the creation of a standard data communication protocol has the potential to save over $56 million annually. This estimate, which is based on an 80 percent chance of success, includes the potential savings from reduced electrical hardware, complexity, and maintenance.

The process to develop a communication standard builds on two existing protocols: LonWorks and the Train Communications Network (TCN). LonWorks, developed by Echelon, is a general purpose control networking protocol used to connect components and systems within one rail car or train set. TCN was originally developed in Europe to allow compatibility between trains operating in different countries.

On-Board Diagnostics

As in bus transit, there are no defined rail standards to monitor, collect and present operating status and fault information. Each new order of rail cars, along with those slated for overhauls, requires an engineering effort by all parties to determine which parameters to monitor, how often to sample data, and how long to preserve the data. The working group in this area is developing a standard approach for systems that would monitor, collect, process and present operating status and fault information for rail vehicles. A standard diagnostic system is projected to save the industry about $78 million annually in maintenance costs.

The most sophisticated on-board diagnostic systems are in place on Boston's Red Line Cars, new cars delivered for service on SEPTA's (Philadelphia) Market-Frankfort line, and cars remanufactured for New Jersey Transit. R142 rail cars being designed for New York and Amtrak's planned high-speed cars will also include a comprehensive specification for an on-board monitoring and diagnostic system.

Helping to promote on-board diagnostics are event recorders. Required by the Federal Railroad Administration (FRA) for use in railroads and commuter rail applications, on-board event recorders are becoming more prevalent in transit applications. The monitoring of train events for accident reconstruction purposes can also be used for diagnostic purposes.

TCIP for Rail Transit

A separate working group is developing data message sets that will be compatible with Transit Communications Interface Profiles (TCIP). Funded by the U.S. DOT, TCIP is a program under ITS that will allow data generated from various public transit sectors to be exchanged with other elements of ITS.

Before the exchange can take place, however, data messages must be clearly defined. The development of standardized data message sets will ensure that terminology used to communicate between trains is understood in the same manner by all ITS participants. Additional informantion on TCIP is provided in Chapter 6.

CHAPTER 4

ELECTRICAL SYSTEM MULTIPLEXING

The term "multiplexing" applies to a broad range of electronic integration. This chapter focuses on electrical system multiplexing, which uses microprocessors and proprietary data networks to control basic on/off electrical devices such as lights, turn signals, horns, and similar "hotel" type functions.

SUMMARY

Transit buses contain many electrical devices that need to be switched on or off depending on operating conditions. As noted earlier, the traditional means of controlling electrical devices is through relay logic. With relay logic, power and ground signals used to activate and deactivate devices are carried through individual "hard" wires. Relays are used to receive electrical current from one switch and "relay" it to another device. Each connection point has the potential for failure, which must be traced step-by-step to discover.

Multiplexing replaces relay logic with a computer-based system to control electrical functions. It performs similar tasks with less wiring and fewer relays, and features its own built-in diagnostic system. The monitoring capabilities of multiplexing also allow it to oversee certain functions and trigger alerts to the operator. Multiplexing is installed as an entire system by the bus builder. Furthermore, its operation is completely invisible to the bus operator.

Multiplexing has been adopted from other industries and uses its own proprietary operating system. Since they perform basic on-off type functions such as activating lights, the proprietary nature of multiplexed systems does not impact electrical products on the bus. For example, the switch that activates a particular device and the device itself are not affected by multiplexing's operating system. As a result, transit agencies can continue to purchase switches and electrical products such as lamps from traditional sources. What they cannot do, however, is exchange components such as microprocessors and modules from one multiplex system to another.

There are two known multiplexing approaches currently offered for bus applications. One system disperses control functions throughout the bus. Another uses a centralized processing system. Despite the differences, multiplexing systems provide many benefits in common. Included are the ability to modify the electrical system without adding wires, relays and connectors, and the use of indicator lamps to simplify diagnostics.

TRADITIONAL ELECTRICAL SYSTEMS

Before describing multiplexing or "mux" in greater detail, a brief explanation of traditional electrical systems will make the benefits easier to understand. To function, each electrical device needs a continuous "circuit" of both power and ground from the battery. Switches and relays are used to "open" or "close" the circuit depending on whether the device is "off" or "on." A relay is nothing more than a heavy-duty switch that receives power or ground from one switch and "relays" it to control (i.e., activate or deactivate) another device.

Relays can also be used to control functions under certain conditions. For example, to help reduce windshield glare, a separate relay can be added to extinguish a single row of lights just behind the windshield whenever the door is closed. The use of relays to control electrical functions, known as relay logic, requires individual wire connections. Figure 4-1 illustrates how four electrical devices are connected in a traditional point-to-point "hardwired" electrical system.

As an increasing number of electrical control functions are added, the number of wires, relays, and connectors also increases. In a 40-foot bus, the vast amount of equipment increases electrical system complexity and bus weight. If one of the many wire connections should come undone and create a loss of continuity because of corrosion, poor crimping, or loose terminals or connectors, it must be traced step-by-step back to the faulty connection.

Additionally, specific features requested by each agency require a different configuration of wires and relays, which adds production time and cost to each bus order. According to one bus manufacturer, the electrical system can consume up to one half the engineering time to design, and up to 15 percent of the vehicle production time to build, install and troubleshoot (38).

MULTIPLEXING: THE BASICS

Multiplexing simplifies the electrical system by replacing the maze of relay-logic control with software. In a multiplexed system, a microprocessor monitors

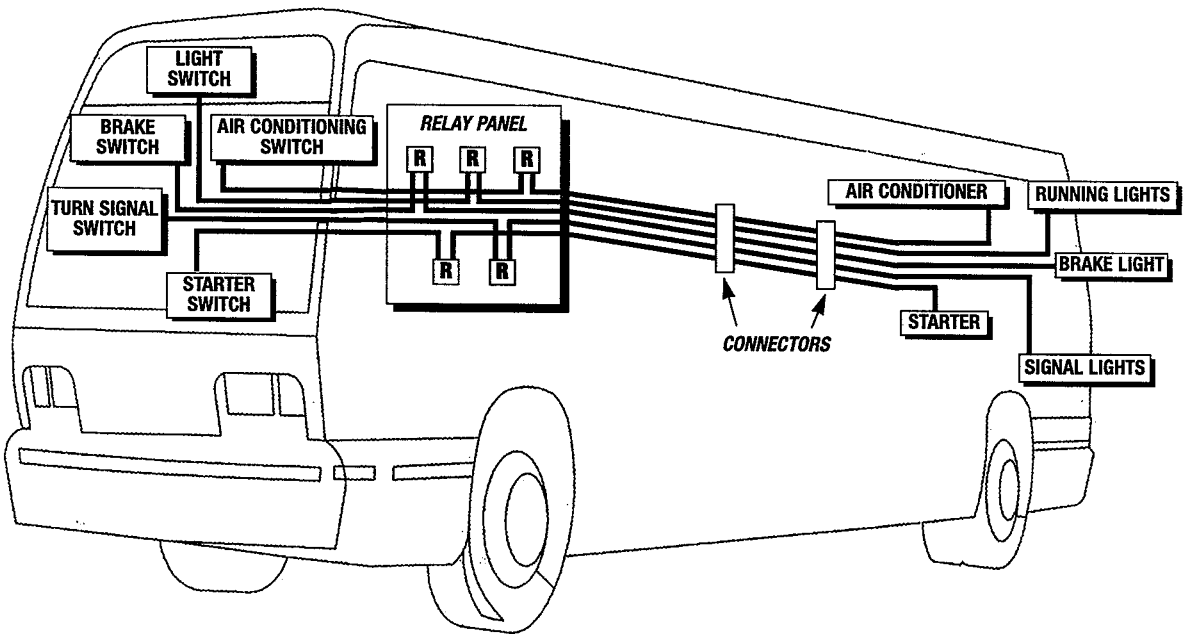

Figure 4-1 Traditional "hardwired" electrical system with separate wires connecting switches, relays, and electrical devices.

switch positions, and controls devices accordingly. Instead of using individual wires and relays to control electrical devices, multiplexing uses its own data network and signaling system.

Essential to multiplexing are the various input/output (I/O) modules strategically located throughout the bus. Typical locations include the operator's area, front door, rear door, and engine compartment. If the operator activates the brake pedal, for example, an I/O module at the front of the bus sends a signal to the main controller (i.e., microprocessor). In turn, the controller signals an I/O module at the rear of the bus instructing it to deliver battery power to the brake lights. I/O modules are important because they process control signals from the multiplexing operating system, and also direct electrical current to specific devices when given the appropriate command. Figure 4-2 illustrates the basic concept of electrical system multiplexing.

MULTIPLEXING: THE DETAILS

There are two popular approaches to electrical system multiplexing: centralized control and decentralized control (22, 39). In a centralized control system a single processor controls the various I/O modules, which collect information and react to commands. In a distributed control system, I/O modules also have processing capabilities and can initiate commands locally for faster reaction time. Both systems use a single cable to send and receive control messages. Centralized control systems use a two-wire cable; distributed control systems use a six-wire cable. To simplify the explanation of multiplexing, a centralized control system will be described in this chapter.

There are three main components to a typical centralized-control mux system: main controller, I/O modules, and the data cable. The main controller serves as the system's "general in charge," continually scanning all conditions and executing commands based on its internal software program. I/O modules are "soldiers in the field," gathering intelligence on the status of inputs (i.e., switch positions), and making the information available to the main controller. The controller then processes all inputs and sends a signal back to the output portion of the I/O modules to execute commands.

Since I/O modules are also supplied with power and ground current from the bus batteries, internal relays within the modules are used to distribute current to specific devices when instructed by the main controller. The relays used in the I/O modules can be solid-state, electro-mechanical, or a combination of both.

A data cable carries messages between the main controller and the I/O modules. It consists of a small number of wires that can send multiple signals in either direction (similar to a telephone line). Signals sent within the wires can emit or be affected by electromagnetic interference or radio frequency interference (EMI/RFI) generated by power lines, radio signals, radar, and various on-board electronics. To protect

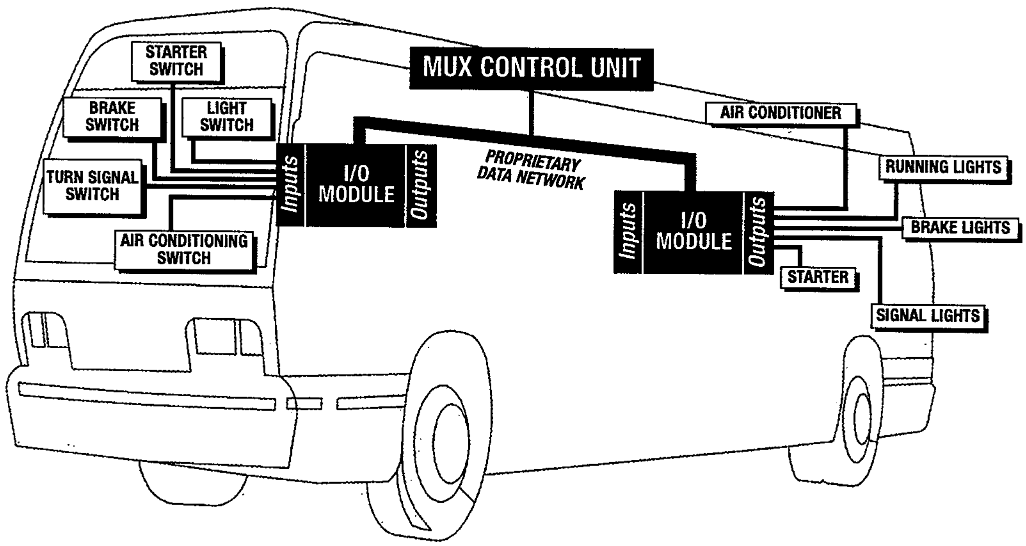

Figure 4-2 Instead of running individual wires to each device, multiplexing uses a controller and satellite modules to control several functions over its own data network.

against EMI/RFI, data cables are shielded to minimize the reception or radiation of electromagnetic energy.

Mux, Start Your Engine

In a mux system the switch that initiates a command and the device that becomes activated remain the same. It is the connection between them that differs. The engine starting circuit is used to describe multiplexing in greater detail.

Traditional Approach

In a traditional wiring system, the starter is activated by sending electrical current through a series of relays to ensure that the engine starts under safe conditions. Relays must be individually wired from the transmission to indicate that it is in neutral, the alternator to ensure that the engine is not already running, and from an engine compartment switch to ensure that a mechanic is not working there. When all relays are activated correctly, continuity exists and electrical current is carried through the wiring to engage the starter.

Multiplexing Approach

Except for the starter switch and the starter motor, mux operates much differently. When the engine switch is depressed, electrical current is sent through a wire to the "input" portion of the closest I/O module. Using the data cable to constantly scan all signals, the controller recognizes that an electrical current is present at the I/O module.

The controller then uses its programmed logic to search for conditions that must exist at other input addresses (i.e., the transmission is in neutral). If the appropriate signals are received, the controller signals the I/O module nearest the starter to engage the starter.

A schematic illustrating how a centralized-control mux system uses battery current and its own signaling system to control electrical devices is shown in Figure 4-3. The starter circuit has been isolated to serve as a representative example.

Those accustomed to reading wiring schematics can follow Figure 4-3 without much difficulty. For others, a brief explanation will help:

- Power (+) (12 or 24 volt) and ground (-) current from the battery is provided over separate "hard wires" to the main controller and each I/O module.
- A two-way cable (i.e., data network) sends proprietary signals to and from the I/O modules and main controller (it does not carry battery power or ground).
- A scanner (part of the main controller) uses the data cable to continually scan the input signals from all I/O modules.
- When the operator depresses the starter switch, power or ground is sent to a specific address on an I/O module located in front of the bus.
- A signal from the I/O module is sent over the data cable to inform the main controller.
- When the controller receives the signal, it uses its programmed logic to scan the inputs from the eutral safety switch and rear-start position switch.

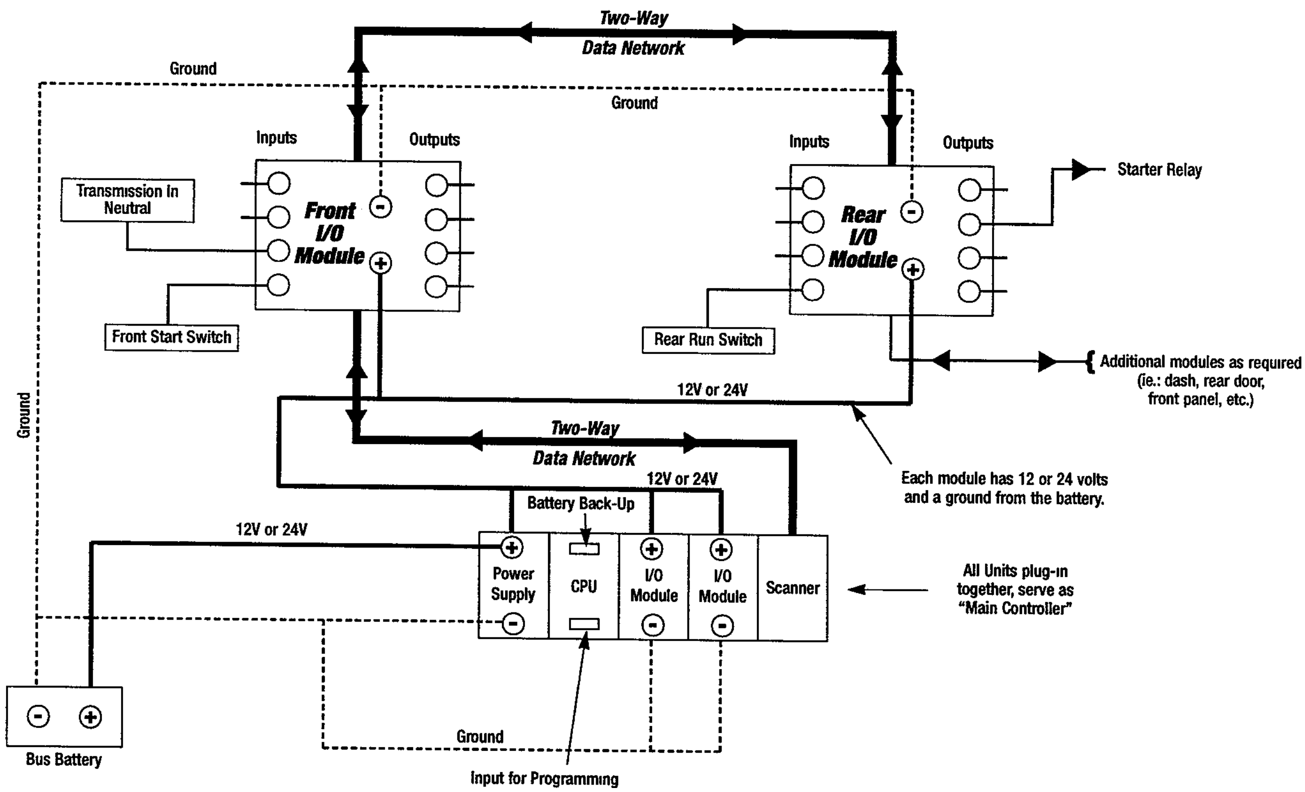

Figure 4-3 ***Schematic showing how multiplexing uses its own data network and the battery's power and ground current to control the engine starting circuit***
(Courtesy of David Harvey, Milwaukee County Transit)

- If all conditions are satisfied, a command signal is sent via the data cable to the output side of an I/O module.
- Once the output side of the I/O module receives the command, relays inside the module direct power to the starter relay.

Ladder Logic

Like other computers, the mux processor uses a program to perform its duties. The program used by mux is called ladder logic. A ladder logic schematic closely resembles a traditional relay-based electrical system schematic with some major differences. Whereas a hardwired schematic shows the actual flow of battery current, a ladder logic schematic represents instructions written for the software application.

Another difference is that in a traditional electrical diagram, devices are either "open" (contacts open, no current flow) or "closed" (contacts closed, current flows through). In a ladder logic program, instructions are either "true" or "false," although the two sets of terms are often used interchangeably.

Figure 4-4 shows the ladder logic of a single control function. Each rung of the ladder represents the condition(s) that must exist — or be "true" — before a particular electrical device can be activated. Read left to right, ladder logic begins with one or more condition instructions or inputs (i.e., switch position is on), and at least one control instruction or output (i.e, energize light). The symbols for frequently used condition instructions include "normally open" (**][**) and "normally closed" (**]/[**). When all conditions are true (i.e., a normally closed condition is in fact closed), logical continuity exists and a control signal is given to energize a particular device.

When any of the condition instructions are false (i.e., a normally closed condition is open), logical continuity does not exist and the control instruction remains in the "off" or de-energized state.

Electrical Changes Made Through Software

One of the most significant benefits of mux is its ability to make changes without running separate wires or adding relays. Instead, changes are programmed into

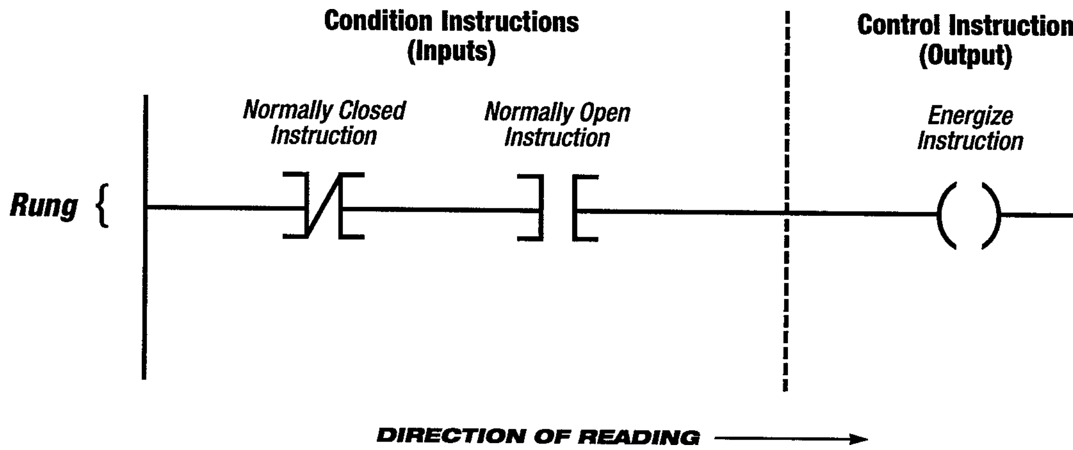

Figure 4-4 ***Ladder logic instructions.***

the ladder logic software using a laptop computer. For example, if an agency wanted to prevent the starter from overheating, the mux controller could be programmed to de-energize the starter after 10 seconds of cranking regardless of the operator's actions. Since changes made to the software program are done on a PC, ladder logic schematics can be printed to keep a current record of bus configurations.

LEDs Simplify Diagnostics

Another benefit of multiplexing is its self-diagnostics capabilities. In a traditional wiring system, the mechanic must use a test lamp or similar instrument at each connection point to determine why a particular device is not responding to a switch being turned on. In a multiplex system, the main controller and I/O modules have light emitting diode (LED) lamps at each input/output address for simple visual inspections. The LED lamps illuminate when the address is active, providing maintenance personnel with a visual indication if signals are being received. When a malfunction does occur, the LEDs provide a quick means of fault detection. Figure 4-5 illustrates how LEDs are used to indicate if signals have been received.

Connecting a laptop computer or hand-held tester to the main controller provides another method of tracking faults. In about 85 percent of all cases, however, visual inspection of the on-board LEDs typically result in fault identification (22). If a failure involves an I/O module or the main controller, they typically are not field repairable and must be removed and replaced as an entire unit.

Two MUX Approaches

There are two known multiplexing approaches offered for North American transit bus use. Both designs have been developed for industrial applications and are readily adaptable for use in transit bus environments. Each uses its own components, along with a

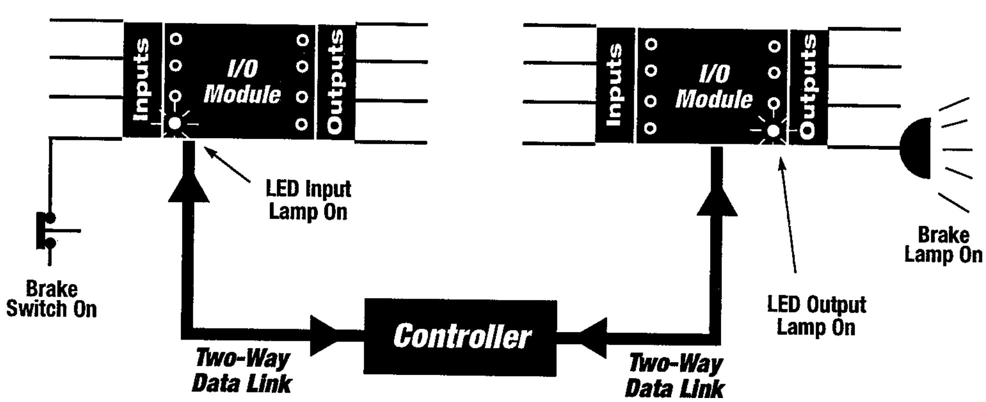

Figure 4-5 ***LED lamps provide visual indication of control signals.***

proprietary communication protocol, to operate. Additional features and characteristics that the two systems share in common include:

- Ability to monitor and control the on/off status of any electrical component;
- Use of LED lamps to indicate input/output status to simplify diagnostics;
- Use of a PC to add specific features to the electrical system without adding wires, relays, and connectors;
- Use of "ladder logic" as the operating program;
- Use of a power supply module to ensure that the system is provided with "clean" power; and the
- Ability to easily plug in additional product-specific components such as I/O modules.

Despite the similarities, there are some major differences. The primary difference is that one system uses centralized control, while the other uses distributed control. Another major difference involves the current load each system can handle without requiring traditional relays. Systems are capable of handling current loads from one amp to 10 amps. After that, additional relays are required.

Gateway modules permit transfer of data between multiplexing's own proprietary data networks and other protocols such as those developed by SAE (i.e., J1708). In addition, robust data networks such as SAE J1939 described in the next chapter may be configured in the future to control electrical functions.

CHAPTER 5

THE ROLE OF STANDARD DATA NETWORKS IN ELECTRONIC INTEGRATION

The last chapter described how multiplexing uses proprietary data networks to control basic on/off switching in the Electrical Level. This chapter describes how standard or "open" networks developed by the Society of Automotive Engineers (SAE) are applied to integrate components in the Drivetrain and Information Levels. Although other networks could be applied, this chapter focuses on SAE networks for four main reasons:

(1) SAE networks are already used in buses to integrate drivetrain components;

(2) The vehicle area network (VAN) program has selected a modified version of SAE J1708 as its choice for Information Level integration;

(3) Transit agencies are writing specifications that include Information Level compatibility with J1708; and

(4) Heavy-duty trucking has successfully applied SAE networks to integrate on-board components, including those relating to vehicle location, communication, and radar collision avoidance.

SUMMARY

The transfer of data between electronic devices usually involves a reference to three terms, which are often used interchangeably: communication protocol, data network, and system architecture. For the purposes of this study, a communication protocol is a set of rules that define how messages are coded and transmitted between electronic devices. A data network is the two-way cable and framework that uses the protocols to deliver messages between vehicle subsystems (i.e., engine and transmission, AVL and farebox, etc.).

System architecture is a much broader framework for information exchange through which larger systems are integrated (i.e., bus and transit agency, transit agency and other municipal agencies, etc.). On a national level, the ITS Architecture described in Chapter 6 seeks to ensure that data will flow in a uniform manner between all ITS elements. On a transit agency level, a well defined architecture permits an efficient exchange of data between buses and all agency departments.

This chapter focuses on data networks, the framework used to exchange data in an orderly fashion between components in the Drivetrain and Information Levels. Networks can be based on varying degrees of proprietary (i.e, closed) or standard (i.e., open) communication protocols. The degree to which networks are open or closed depends upon how they interface with seven layers of a reference model developed by the International Standards Organization (ISO). A fully open network is one where documentation for all seven layers is made available to any supplier. A fully closed network is one where all interface specifications are proprietary — not available for public use.

Although a data network is described as "open," it does not necessarily use all seven layers of the ISO reference model. For example, SAE networks are considered open yet J1708 uses only three layers, which was sufficient to meet all network needs for trucks and buses at the time. SAE J1939, developed for new-generation drivetrain components, makes use of all seven layers, as do other networks. The better defined the network, the more flexible it can be in accommodating new applications.

Regardless of how well defined, open data networks allow components of different makes to be exchanged in a "plug and play" fashion. This standardized approach allows the end user to choose from a variety of products. It also allows components to be upgraded easily, an important consideration for a 12-year bus life cycle.

Until recently, most Information Level electronics have been designed around proprietary systems. However, a program is underway to create a standardized VAN specifically for integrating Information Level components. VAN is based on the existing SAE J1708 data network, which is being modified for transit bus use.

Some question the ability of J1708 to handle Information Level integration. Proponents, however, argue that the question is not whether J1708 is the best network available — clearly there are faster and more flexible networks to choose from. The real question is whether J1708 is the most appropriate and cost-effec-

tive solution for bus applications. The question of J1708's appropriateness for bus applications will (hopefully) be answered in the near future. The VAN section of Chapter 6 provides additional information on J1708's application to transit buses.

An overview of data networks reveals why they were developed, how they operate, and why they are changing. The insight is especially useful as agencies attempt to integrate components found in the Information Level. Unlike multiplexing and drivetrain components integrated by the bus builder, Information Level integration requires greater involvement by the transit agency.

OPEN SYSTEMS INTERCONNECTION (OSI) REFERENCE MODEL

The Open Systems Interconnection (OSI) reference model was developed by the International Standards Organization (ISO) to standardize the communication of data between computer systems. This universal model defines the specific procedures, or "protocols," that developers of data networks must follow when transferring information between electronic devices. The reference model is divided into seven different interface "layers." The layers define the manner in which a system, subsystem or component can interpret information transmitted to it by another. Included are requirements for:

- Interfacing a device on the network to a cable (i.e., Physical Layer);
- Interfacing the cable with higher levels of the subsystem, including how source and destination fields will be identified (i.e., Data Link Layer); and
- Interfacing specific software applications to the open systems interconnection environment, including provisions for file transfer (i.e., Application Layer).

All seven layers and related functions of the OSI model are summarized in Appendix B. A fully open network is one where documentation for each of the seven layers resides in the public domain. A fully closed network is one where interface specifications are proprietary and not available for public use. While some networks use all seven layers of the OSI model, others do not. The better defined the network (i.e., uses many or all seven layers with specifications for each available for public use), the more flexible the network can be in accommodating new applications.

The concept of open data networks is important because it allows components of different manufacture to be exchanged in a "plug and play" fashion. A video cassette recorder serves as a good analogy. Regardless of the brand, any VCR can "plug" into a television to "play" a video tape. Open access to the network is significant because it gives the end user a variety of products to choose from at competitive prices. It also provides additional flexibility when upgrading to new technology. On the other hand, closed networks restrict access to the network and only allow certain manufacturers to use it.

Several reference books are available that provide additional information on the OSI model, along with the open-architecture networks developed from it (40,41,42,43).

SAE FAMILY OF DATA NETWORKS: AN OVERVIEW

SAE data networks developed for heavy-duty trucks and buses conform to certain protocols set forth in the OSI model. Before describing each SAE network in detail, a brief overview and chronological perspective offers insight into why certain SAE data networks are being applied to different bus levels.

In 1986, SAE began the task of standardizing the exchange of data for heavy-duty trucks. The result was SAE J1708, which defines the basic hardware and conditions required for on-board data exchange (44). With the J1708 backbone in place, SAE completed the network with J1587 to add general on-board information sharing and diagnostic functions, thus making J1708 an operable network (45). Whenever J1587 is mentioned, it is assumed that J1708 is included (i.e., J1708/J1587).

Using a home computer as an analogy, J1708 determines how the color monitor and keyboard will connect to the computer, while J1587 defines how each component will function. Originally intended for heavy-duty trucks, J1708/J1587 was adapted for bus use in 1992.

Since drivetrain component messages consume about 70 percent of the network's capacity, SAE developed J1922 as another protocol that could operate over a J1708 network (46). The J1922 addition to J1708 was developed exclusively for first-generation engine, transmission, and retarder functions. Use of a separate network was deemed necessary due to the safety critical nature of drivetrain components, and to improve the data throughput rate. First applied to trucks, SAE J1922 was also used on buses.

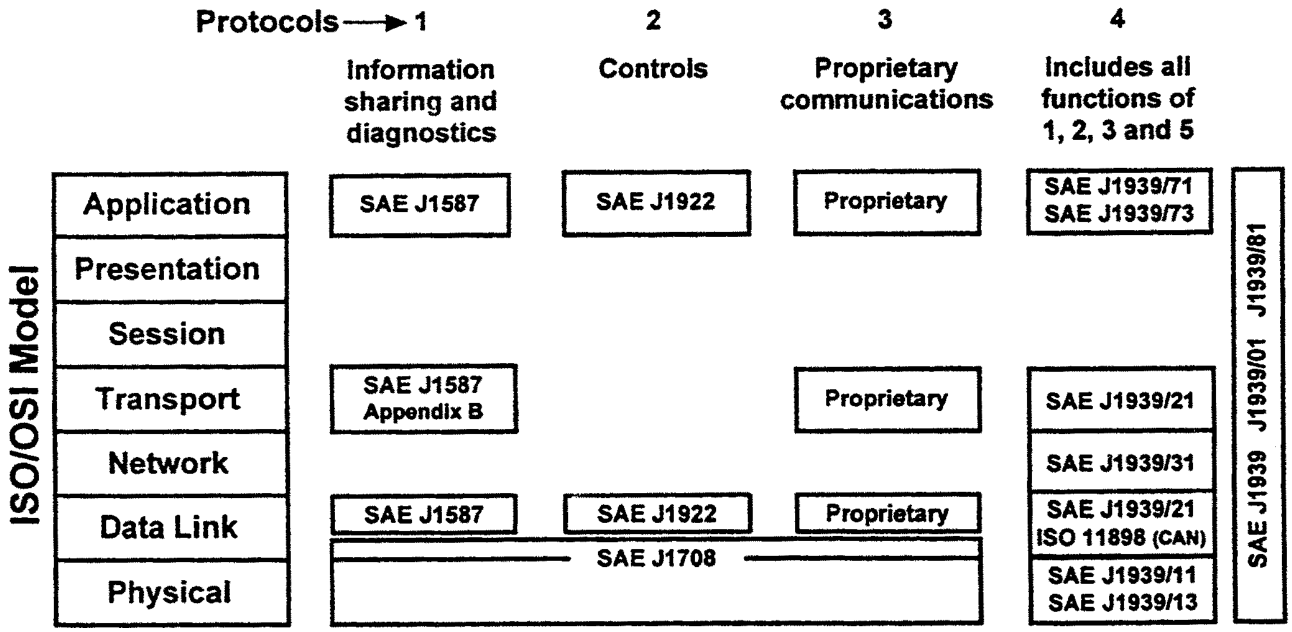

Figure 5-1 *SAE Documents mapped to the OSI model. (Courtesy of Cummins Engine Company)*

In the constantly changing world of electronics, the SAE J1708 family of networks became inadequate for advanced drivetrain integration. For one, J1708 lacks the speed necessary to handle some of the complex data interactions inherent with anti-lock brakes and traction control. Further, the growing number of electronic components added to the vehicle requires additional J1708 networks to accommodate them, adding cost and complexity to vehicles. To resolve this, SAE is developing a new data network called J1939, which is being released as several documents because of its complexity (47).

The J1939 network is capable of handling all of the requirements currently satisfied by J1708/J1587/J1922 with excess capacity to address future requirements. Drivetrain components are the first to use J1939 as a replacement for J1708/J1922. SAE J1939 is based, in part, on the Controller Area Network (CAN) data network developed and licensed by Bosch for European vehicles (48).

Figure 5-1 shows the various SAE documents mapped to the OSI model (49). As Figure 5-1 illustrates, SAE J1708 and J1587 interface with three of the seven OSI layers, which at the time of their development were deemed sufficient to meet data communication needs. The more robust J1939 network spans all seven layers.

In addition to data networks, SAE has issued a recommended practice concerning environmental conditions that electronic equipment must be capable of enduring. Called J1455, it defines test methods for temperature, humidity, dust, washing, mechanical shock, and other factors pertaining specifically to the environment of truck and bus electronic systems (50).

3-Speed Data Transmission

SAE data networks developed for heavy-duty trucks and buses are classified by their data transmission rate or speed. Table 5-1 shows the class, speed, application, and corresponding designation of critical SAE data networks.

The use of a high-speed Class C data network such as J1939 is 26 times faster than a low-speed Class A network like J1708, which is analogous to driving an automobile at 100 mph versus 4 mph. This difference in travel time, referred to as latency, is critical for safety and real-time control functions. For example, when the ABS system detects a locked wheel it must have the required speed to transmit, receive, and process data quickly to avert a potentially dangerous situation. Delays in data transmission could cause a wheel to remain locked for an extended period of time, resulting in a potentially out-of-control condition. As a result, most drivetrain components are now being integrated around the high-speed J1939 network.

Is J1708 Fast Enough?

One of the issues surrounding the applicability of J1708 to Information Level integration involves its speed. Some argue that the use of a low-speed Class A

Class	Speed	Application	SAE Data Network
A	Low speed, less than 10,000 bits/second	1) Used in the "Drivetrain" Level for 1st-generation engine, transmission, etc. 2) Limited "Information" Level application for AVL, headsigns, fare collection, etc	1) Typified by the J1708 family of protocols including J1587 & J1922 2) Typified by J1708/J1587 used in the Vehicle Area Network (VAN)
B	Medium Speed, from 10,000 to 125,000 bits/second	Used for general data sharing and diagnostics in automobiles	Typified by J1850
C	High Speed, from 125,000 to 1,000,000 bits/second or greater	Used in the "Drivetrain" Level for next-generation control of engine, transmission and brake systems	Typified by J1939

Table 5-1 The three classes of SAE data networks based on speed.

network such as J1708 is adequate and cost-effective for integrating AVL, destination signs, fareboxes, and similar components. Others claim that it is not fast enough, especially when sending data in real time.

Proponents of J1708 contend that data transferred back to the transit agency in real time is limited by the radio system, not the on-board data network. With a transmission speed of 9600 bits per second (baud), the low-speed SAE J1708 data network is said to be more than capable of transferring data over a bus radio system with a typical baud rate of 4800. Additional information concerning SAE J1708 and its transmission speed is provided in the VAN section of Chapter 6.

No Main Controller

Unlike multiplexing described earlier, SAE data networks do not use a microprocessor to manage data communications among the various components. Instead, the electronic control module (ECM) of each component is equipped to manage the flow of data according to established protocols.

Although each device is responsible for managing data over the network, a microprocessor such as a VLU can be added to the network like any other device. It too can "listen" to messages transmitted over the network. With its abundant processing capabilities, the VLU can be programmed to make use of data in a variety of ways. For example, it can monitor several operating conditions, store them in memory, and send alarms in real time over the radio to the agency's facility.

SAE NETWORKS: THE DETAILS

SAE J1708

As noted earlier, J1708 identifies the minimum hardware and procedural requirements for routing messages over the network. It establishes a method for determining:

- Which device is communicating (i.e., engine, farebox, etc.);
- The length of time that each device is allowed to communicate;
- Which device has priority in accessing the network when two try to gain access simultaneously; and
- That the message was received correctly should there be problems in transmission.

All on-board electronic components are connected to the network with a pair of twisted wires (i.e., cable) that carry data in both directions. SAE J1708 specifies the requirements for the cable itself, along with connectors, acceptable voltage and current limits, and number of subsystems allowed on the network. Up to 20 subsystems are permitted to send messages over the network. When one wants to transmit a message, it must wait until the network is idle (i.e., not carrying another message for a specified period of time). Once the network is free, the message is sent using a priority-ranking protocol.

If two or more messages are sent simultaneously, a contention resolution procedure determines which message gains access first. The procedure begins by cancelling both messages. After a specified delay period, the message with the highest priority is allowed to re-access the network first. The secondary message is then allowed to regain access to the network when idle. This contention resolution procedure of cancelling both messages delays the transmission of data, which makes J1708 unacceptable for some time-sensitive control functions such as ABS.

The number of individual SAE J1708 networks that can exist on a vehicle is unlimited. It is not uncommon for a modern transit bus to have multiple J1708-based networks: one (or more) to integrate drivetrain-related components, and one to integrate Information Level components.

SAE J1587

SAE J1587 completes J1708 by defining the protocol that devices on the network will use to communicate. For example, something as simple as a date (i.e., 02-11-98) can not be communicated accurately unless it was known which digit pairings correspond to the month, day and year. SAE J1587 clearly defines how messages are transmitted and received by each device on the network.

Examples of the types of messages initiated and received by electronic components connected to the J1708/J1587 network include:

- Vehicle and component information relating to operating performance status and diagnostics;
- Routing and scheduling information, which relates to the planned or actual route of the vehicle, current vehicle location, and ridership data;
- Information pertaining to operator activity; and
- Freight status and billing activities (trucking use only).

Each message has an assigned priority based on an eight-level scale. This allows urgent messages to have preference over non-critical correspondence. SAE J1587 also supports file transfers for uploading and downloading larger amounts of data between the bus and remote locations. The protocol is designed to transfer files when the network is idle to avoid tying up the data network from normal message traffic.

In addition to operational messages, J1587 also transfers component performance data including an indication if a device is functioning properly or experiencing failures. SAE J1587 also "reads" the serial number for each device, allowing software and data revisions to be made easily over the network..

SAE is constantly defining new messages for J1587 through requests from its truck and transit members. New message sets being defined for transit include those for ITS-related devices such as fare collection, AVL, traffic priority, next-stop annunciators, on-board signage, and operator control heads.

SAE J1922

SAE J1922, which also requires a J1708 backbone to operate, is used on the first generation of drivetrain components. While appropriate for early integration, SAE J1922 is becoming obsolete because its slower speed cannot accommodate the number of data messages generated from the growing number of drivetrain control functions. In its place, manufacturers have applied the faster-speed J1939 network.

Until all equipment is compatible with J1939, however, bus manufacturers typically run a J1939 network alongside various combinations of the J1708-based networks. As noted earlier, operation of these multiple networks is seamless to the transit agency.

SAE J1939

SAE J1939, "Recommended Practice for Serial Control and Communications Vehicle Network," is a high-speed Class C general purpose network. It is being developed to handle information sharing, diagnostics, multiplexing, and specific communications that product manufacturers want to keep as proprietary. Based in part on the European CAN protocol, it will satisfy all of the functions currently performed by the J1708 family of data networks with excess capacity to handle future needs. Initial work on J1939 began in 1986. Today, much of this network is complete.

Manufacturers of drivetrain components are the first to implement J1939 on their most recent product offerings. The move to J1939 is needed to accommodate the real-time requirements of ABS and traction control, as well as the growing number of drivetrainrelated control functions.

SAE J1939 has a data rate of 250,000 bits per second, making it much faster than J1708. SAE J1939 also permits a connection of up to 30 units compared to a maximum of 20 for a J1708 network. Further, J1939's non-destructive message arbitration process adopted from CAN ensures that data transmission time is fully utilized.

SAE uses a labeling format where all documents begin with J1939, followed by a slash and a two digit number (i.e., J1939/12). In most cases, the first digit corresponds to the applicable OSI layer, while the second denotes additional capabilities or an alternate solution. Figure 5-1 shown earlier maps the various J1939 documents to the seven OSI layers. Appendix C lists the titles for the various J1939 documents as defined by SAE (49).

Once J1939 is fully developed, it will likely be configured to include other control functions as well. Future applications for J1939 may include power control functions currently handled by electrical system multiplexing, service tools, diagnostics, and operator instrumentation functions. Heavy-duty trucking will be the first to expand the use of J1939. Concerning transit buses, J1939 is already being applied to drivetrain integration. Application to the Electrical Level (i.e., multiplexing) may follow, depending on J1939's success in trucking and how current multiplexing systems develop. Information Level integration, however, continues to center around VAN using a modified version of SAE J1708 as its foundation.

SAE J1455: Environmental Practices

SAE J1455 is not a data network. Instead, J1455 serves as a Recommended Practice (RP) to aid designers of electronic systems and components by providing guidance that may be used when developing environmental design goals (50). The RP covers climatic, dynamic, and electrical environments that influence the performance and reliability of electronic equipment used in heavy-duty vehicles such as trucks and buses.

Environmental factors and test methods are organized under 13 headings. Included are: temperature; humidity; salt spray; steam cleaning and pressure washing; altitude; mechanical vibration; shock, dust, sand and gravel bombardment; and other conditions. The RP combines some of these factors to ensure that real life environmental conditions are duplicated. For example, the suggested test method for humidity includes a combination of both high- and low-temperature exposure.

Vehicle environment is classified by specific areas that include the engine compartment, interior, chassis, and exterior portions of the vehicle.

SAE NETWORKS AND DRIVETRAIN INTEGRATION

All electronically controlled drivetrain components installed in U.S. buses exchange data over one or more SAE-developed networks. The use of dedicated networks to support drivetrain components ensures protection from components and systems not considered vital to the vehicle's driveability.

Manufacturers are currently in a state of transition regarding the application of SAE networks, producing equipment that supports the transfer of data on the J1708 family of networks (i.e., J1587/J1922) and the new J1939 standard. Communication ports on each component convert J1708-type data into J1939 data and visa versa. As drivetrain components become updated and more experience is gained with J1939, J1708-related connectors and circuitry will not be needed.

Exchanging data between the engine, transmission, retarder, ABS/traction control system, accelerator pedal, and brake pedal improves both driveability and safety. Instead of acting as autonomous units, driveline components can perform tasks in unison. For example, when the ABS system reacts to a locked wheel, it can also request that the braking effect of the retarder be turned off to help prevent skidding.

The illustration of Drivetrain Level integration shown in Figure 5-2 has been simplified with a single J1939 network. In fact, multiple networks could be used to support the exchange of drivetrain-related data in a seamless manner.

SAE NETWORKS AND INFORMATION LEVEL INTEGRATION

Developed specifically for truck and bus applications as an open network, SAE J1708/J1587 can serve as a logical platform for standardizing the exchange of data between components typically found in the Information Level. The integration could also be accomplished through the application of other open networks, a proprietary network, or a combination of the two. Until recently, the integration was based on proprietary networks. However, some manufacturers and integrators are actively marketing components and systems that are compatible with J1708. Others are taking a wait-and-see approach to determine which network emerges as the industry norm.

Efforts to standardize the integration of Information Level components around J1708 are being undertaken by the Vehicle Area Network (VAN) program. Several VAN demonstrations are underway at agencies including Houston Metro, Ann Arbor Transportation Authority, Los Angeles County MTA, and MTA New York City Transit (21, 51).

An integral component of VAN is the on-board VLU microprocessor. In a typical installation, the VLU

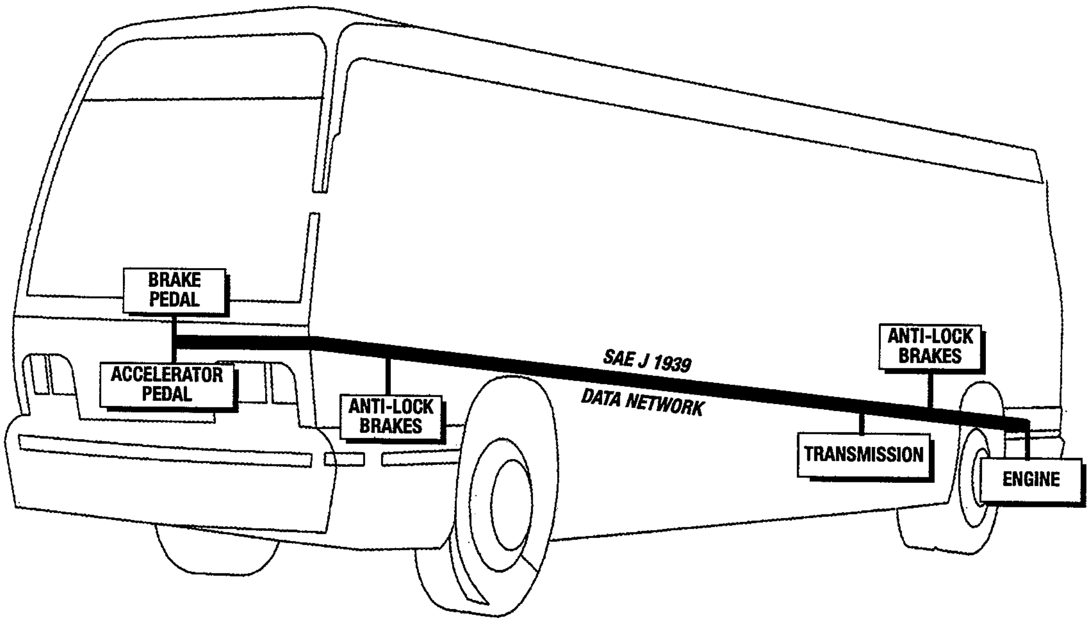

Figure 5-2 Drivetrain integration achieved through SAE J1939.

is a central component of the AVL system. In other applications where AVL is not used, the VLU is a stand-alone device such as an event recorder. A VLU could also be used as a central processor for a next-stop annunciator system that includes future capabilities for vehicle location and component integration.

The use of a data network such as J1708/1587 to exchange information between AVL, VLU, fare collection, radio, passenger information, and other systems provides a variety of opportunities to enhance bus service. Examples of functions made possible through integration include:

- Combine passenger information systems with AVL to provide automatic next-stop audio and visual announcements;
- Combine fare collection with passenger counters, passenger information systems and AVL to identify passenger trends more accurately;
- Combine on-board cameras and AVL to store video images on-board for review at a later time, or send emergency-related images in real time to security personnel; and
- Combine the health-monitoring capabilities of vital on-board components with AVL to send certain fault alarms in real time.

An example of components integrated through a common data network is shown in Figure 5-3. A complete review of the potential benefits offered by Information Level integration is provided in Chapter 7.

OTHER DATA NETWORKS

Although Figure 5-3 uses J1708 as an example, a number of other data networks (open or proprietary) can be used to integrate components. Known data networks used in American and European transit bus applications are summarized below.

CAN

The Controller Area Network (CAN) was originally developed and licensed by Robert Bosch GmbH for the European automotive market as a means of integrating electronic systems on automobiles. CAN has a fast response time and high reliability, making it suitable for demanding applications such as anti-lock brakes and air bags. The versatility of CAN has caused it to be adopted by other data networks as well. Examples include the DeviceNet systems manufactured by the 207 members of the Open DeviceNet Vendor Association (ODVA) (52). In fact, SAE's J1939 network is based in part on CAN.

Like SAE J1708, CAN provides a communication link between electronically controlled components using a serial data networking system. However, whereas the J1587 message-set extension of J1708 is based on an open protocol, each CAN implementation consists of a variety of message sets developed for specific applications. Although the term "CAN" is used uni-

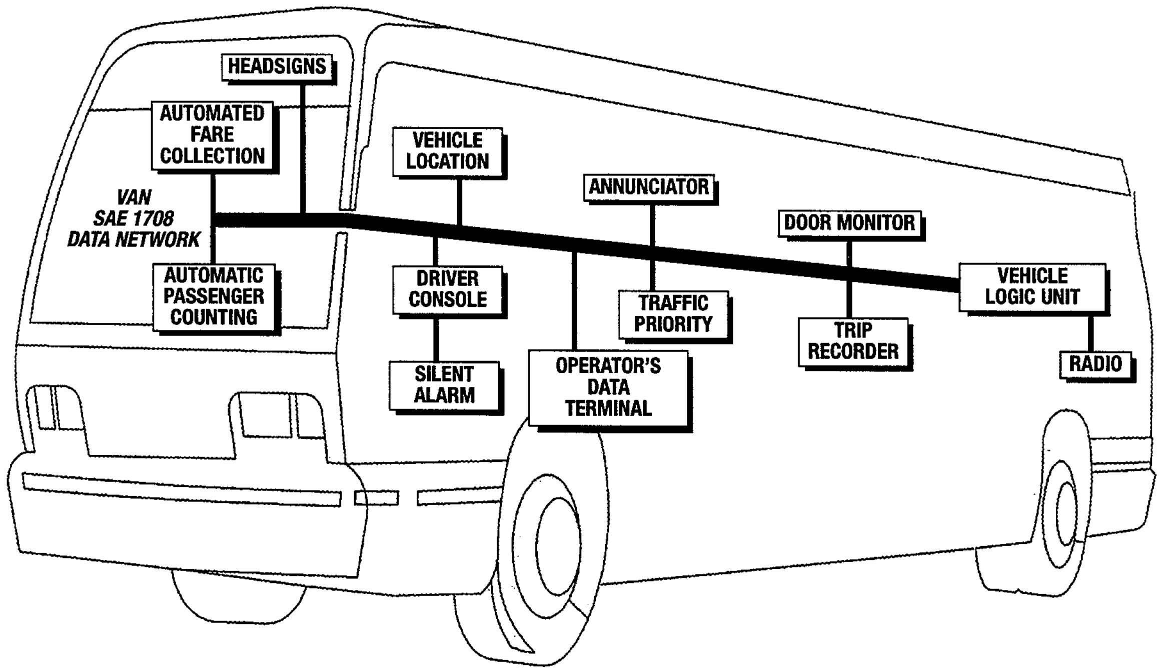

Figure 5-3 Information Level Integration designed around a J1708-based Vehicle Area Network.

versally, several manufacturers produce different CAN products which cannot be interconnected.

Each CAN chip is a processor in its own right, installed within the electronic control module (ECM) of each device to help relieve the ECM of its communications processing duties. As a front-end processor, CAN is analogous to a secretary that sorts mail and screens telephone calls. The ability of CAN to relieve the ECM of duties is vital, especially as the number of messages transmitted per second on the network increases.

A portion of SAE's J1939 data network is based on the CAN protocol. As an advocate of open standards, SAE could not base its J1939 network on proprietary protocols. Instead, it has taken certain aspects of CAN and standardized applications for heavy-duty truck and bus use.

CAN Application to German Buses

The German transit bus industry, organized under the Verband Deutscher Verkehrsunternehmen (VDV), is adopting different-speed versions of the CAN network for application to three bus levels (53). This three-tier approach is consistent with electronic integration in U.S. buses. The first level, called the "system bus," applies to engine management, braking, and other drivetrain-related functions. This level, which uses a fast-speed CAN for drivetrain integration, is capable of transmitting more than 125,000 bits per second.

The second "vehicle bus" level uses a slow-speed CAN network to handle basic on-off control functions of the electrical system (i.e., multiplexing). In the third CAN level, called the "information bus" (which refers to the integrated on-board information system or IBUS), VDV is pursuing the use of a slow-speed CAN network (53).

The VDV is also considering a separate slow-speed CAN protocol dedicated exclusively to the operator's workstation (54). Another option being considered by the VDV for the future is to combine the slower-speed CAN networks into a single network.

Concerning diagnostics on CAN, VDV has adopted an industrial standard known as "CAN in Automation" (CiA). This open standard allows components from different manufacturers to share the same diagnostic network (54).

LonWorks

In addition to networks developed by SAE and CAN, there are several networks available on the market today that may have an influence in the future. One is LonWorks from the Echelon Corporation, used primarily for commercial building and industrial control markets (55). It is also used in rail car applications for electronically controlled pneumatic braking systems and automatic train controls. Some limited-production luxury motor coach manufacturers also use LonWorks to integrate the control of many on-board electrical and electronic amenities. The LonWorks protocol makes use of all seven layers of the OSI reference model, providing nearly complete flexibility in system integration. It uses a chip designed by Echelon and manufactured by Motorola and Toshiba.

ITS Networks

SAE's Intelligent Transportation System (ITS) Division is developing an ITS Databus (i.e., data network) that can work in parallel with existing automotive electronics (56). SAE is also working on four ITS Safety and Human Factors projects (57).

Market costs, technology, business issues, service support, parts availability, and other issues will dictate whether on-board data networks such as CAN, LonWorks and others will become attractive enough to consider them for use in transit bus applications.

NTCIP/TCIP

If ITS is to function as a truly integrated transportation system, all elements such as cars, buses, highways, and commercial vehicles must be able to exchange data in a similar fashion. However, it would be nearly impossible to require all ITS-related functions to use the same communication protocols and networks. Instead, the U.S. DOT is funding a project known as the National Transportation Communications for ITS Protocols (NTCIP).

NTCIP is not a data network like SAE J1708, J1939, CAN or LonWorks. Instead, NTCIP will provide a family of interfaces to serve as "connections" to the various data networks used in dissimilar transportation industries. The portion of the program responsible for developing data interfaces for public transportation is called the Transit Communications Interface Profiles (TCIP).

TCIP interfaces will allow transit agencies to collect on-board data over a network such as VAN/J1708 and convert them into a standard TCIP format. Data could then be exchanged with other departments within the agency that may store data in different formats. Data could also be exchanged with other ITS operating entities such as traffic management centers (58,59). Additional information on NTCIP, TCIP and VAN is provided in the following chapter.

DATA NETWORK REVIEW

Transit buses currently apply data networks to three vehicle levels:

(1) Multiplexing in the Electrical Level to control discrete on/off type power control functions using proprietary communication protocols with transmission rates of about 38,000 to 57,000 bits/second;

(2) The Drivetrain Level, which integrates the engine, transmission, retarder, and brake systems using a combination of SAE networks, the J1708 family of networks with transmission rates of 9,600 bits/second, and the new J1939 network with a 250,000 bit rate; and

(3) The Information Level, which integrates AVL, fare collection, radio/communication, and other systems using either SAE J1708/1587, a proprietary communication network, or a combination of the two.

Despite the application to three distinct bus levels, each network does not function autonomously. Data between them can be exchanged through the use of a gateway, which further expands the integration process. A gateway is an electronic module that connects two data networks by converting the messages into the appropriate format. The sharing of data between the various bus levels provides increased functionality, allowing the bus to operate as an entire system.

TCIP is an example of a gateway technology, allowing on-board data to be transmitted to various ITS field locations in a standard format, thereby making bus transit part of a larger transportation system.