Report No. FTA-WV-26-7000-96-1

U.S. Department
of Transportation
Federal Transit
Administration

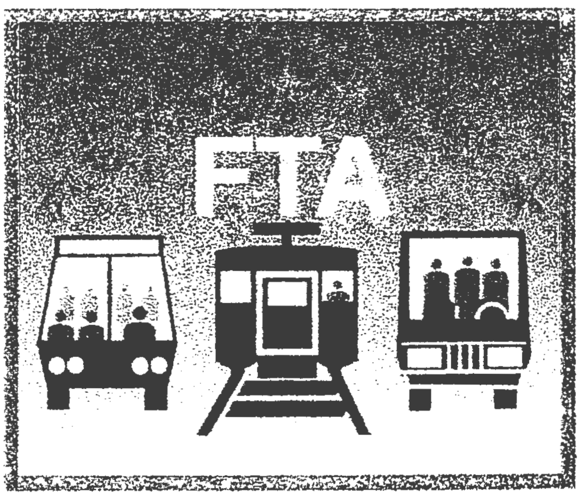
MORGANTOWN PERSONAL RAPID TRANSIT SYSTEM COMPUTER UPGRADE STUDY

Prepared by

The Boeing Company

West Virginia University Research Board
Morgantown, West Virginia

May 1996



Office of Research, Demonstration and Innovation

Report No. FTA-WV-26-7000-96-1

U.S. Department of Transportation
Federal Transit Administration

MORGANTOWN PERSONAL RAPID TRANSIT SYSTEM COMPUTER UPGRADE STUDY

Prepared by

The Boeing Company

West Virginia University Research Board
Morgantown, West Virginia

May 1996

Office of Research, Demonstration and Innovation

Technical Report Documentation Page

1. Report No.	2. Government Accession No. (NTIS)	3. Recipient's Catalog No.
FTA-WV-26-7000-96-1		UMTRIS/FTA SECTION

4. Title and Subtitle	5. Report Date
Morgantown Personal Rapid Transit System Computer Upgrade Study	
	6. Performing Organization Code
7. Author(s): Richard E. Alberts, Marilynn B. Goo, Robert J. Schroder, Paul D. Weis	8. Performing Organization Report No.
9. Performing Organization Name and Address: West Virginia University Research Corporation, Personal Rapid Transit, 99 8th St. P.O. Box 6565, Morgantown, WV 26506-6565	10. Project or Grant No.
	11. Contract or Grant No. WV-26-7000
12. Sponsoring Agency Name and Address: U.S. Department of Transportation, Federal Transit Administration (FTA), 400 7th Street, S.W., Washington, D.C. 20590	13. Type of Report and Period Covered: Final Report
	14. Sponsoring Agency Code: TRI-20

15. Supplementary Notes

Boeing Defense and Space Group, Information and Electronics Systems Division P.O. Box 3999, Seattle, WA 98124-2499, under contract to WVU Research Corp.

16. Abstract

This report describes the present Morgantown Personal Rapid Transit (M-PRT) computer system problems and defines architecture, operating system and new technology alternatives that could potentially be used to upgrade the computers and software. Each of these alternatives is evaluated, resulting in a recommended upgrade approach. Cost and schedule projections for this recommended approach are also included.

17. Key Words	18. Distribution Statement
Fixed Guideway, Morgantown PRT Computer Platforms, Software Rehosting, Operating System, Communication-Based Control, Train Control	– Report available to the public through the National Technical Information Service (NTIS) 5285 Port Royal Road Springfield, Virginia 22161 (703) 487-4650

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price (NTIS)
unclassified	unclassified	86	

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

EXECUTIVE SUMMARY

For over twenty years the Morgantown Personal Rapid Transit (M-PRT) system has been providing efficient service to the students of West Virginia University (WVU) and the people of Morgantown. M-PRT was a state-of-the-art system at its conception and still remains one of the most advanced public transportation systems in the U.S. By early 1993, WVU recognized that immediate planning and action to correct the problems of wear out and technology obsolescence of the computer system were required. To develop a solution, M-PRT Operations and the WVU Research Board initiated the M-PRT Computer Upgrade Study. Boeing Defense & Space Group, the original M-PRT system integrator, was awarded the study. The study was conducted, in a large part, by people who were involved in the original design and deployment of the M-PRT computers and software. Their recommendations are based on knowledge of present technology, a thorough understanding of how M-PRT works, and a desire to provide a capability that will enhance present operations.

There were two basic parts to the study. The first was to evaluate commercially available computer platforms, operating systems, and high order languages and choose a combination best suited for rehosting the existing M-PRT operational software. Most of the existing software was built using PDP 11 assembly language. The evaluation led to the following recommendations:

- Pentium (X86) platforms with a dual Central computer and single station computers
- VXWorks, pSOS+, or VRTX real-time operating system
- Automated translation to ANSI C programming language for compilation using a C++ compiler
- New code for the Central Applications Program (CAP) and Passenger Station Applications Program (PSAP) to drive programmable boarding displays and to implement circulation mode operations
- Extensive laboratory testing of the rehosted system using a real-time simulation.

This new system will be significantly less complex and more reliable than the existing dual-string system. The cost of computer maintenance, whether it is performed by WWU in-house or by a vendor, will be a fraction of the $68,000 per year currently expended on the Digital Equipment Corporation service contract. The system can be upgraded in a little over 15 months. The estimated cost of the upgrade is $5.3 million.

The second part of the study was to evaluate existing and new technologies and determine if it makes sense to incorporate any of them into the M-PRT. The study team contacted a large number of companies and transportation system operators: After reviewing a large amount of data, we concluded that:

- A substantial system engineering effort is required to retrofit the M-PRT system with any new control system technology
- There are no operations and maintenance (O&M) advantages to be gained from technology used on existing transit systems other than to be aware of lessons learned from operational experiences.
- There are potential O&M advantages to be gained from the use of communication-based control technologies being developed for rail applications. However, due to the developmental nature of the majority of this technology, it is far too early to recommend a specific system for implementation.
- Most of the communication-based technologies could be overlaid on the existing M-PRT system for limited demonstration and testing

(This sheet is intentionally blank.)

1. INTRODUCTION

1.1 Purpose

The purpose of the M-PRT Computer Upgrade Study is to evaluate the various options available for upgrading the existing M-PRT computer control system to a computing architecture that will satisfy the system goals for safety, reliability and maintainability. Two basic alternatives were identified by the customer: (1) replace the existing hardware platform and to adapt the computer software sub-system to this selected hardware design, and (2) replace the existing control system with a commercially available technology or a communication-based signal system technology presently being developed by numerous manufacturers.

1.2 Scope

This document describes the evaluation performed by Boeing Defense & Space Group to address the study objectives. In the evaluation we defined the problem definition in more detail (section 2), identified and screened alternative solutions (section 3), and evaluated the best candidates in detail (section 4). We developed an approach for converting and retesting the software (section 5). We also prepared a baseline configuration with a rough order of magnitude (ROM) cost estimate and implementation time line (section 6). The computers and computer peripherals, special purpose equipment (SPE), computer software, and computer to computer communications equipment are considered to be within the scope of this study. Others items such as the destination select units and vehicle command and control subsystems are outside the scope of the study.

1.3 Background

The computer control and communications of the M-PRT was designed and implemented using computer hardware technology of the 1970's. Although it has been operating since 1975, the M-PRT is still the "most technologically complex system in existence."[1] With minor exceptions, original computer equipment is still in use and has become increasingly difficult to maintain.

The existing redundant computing system, figure 1, consists of dual strings of Digital Equipment Corporation (DEC) PDP 11 computers: PDP 11/55's at central and PDP 11/40's at the six stations. In addition to the processors, the central computer complex contains the man/machine interface equipment and data collection media. Each of the two central computers communicates with the other central computer and with each of the station computers in its string. Central computers communicate with station computers via dedicated twisted pair lines and 19.2 kilobit/second dedicated line modems running at 2400 baud. A remote bootstrap system allows central to download software to the station computers without assistance from the remote sites.

The station computer systems contain special purpose equipment (SPE) required to interface the dual string computers with the single string guideway control and passenger equipment electronics. The SPE provides the capability for simultaneous operation and/or automatic switching of the two computers with the system devices. There are three basic types of SPE. One type is used to input data from the destination select units (DSU), the presence detectors (PD), and the vehicle to guideway frequency shift key (FSK) downlink messages. The second type is used for output of the collision avoidance safetone loop control and vehicle uplink messages. The third is used for control of the passenger boarding displays.

---

[1] "Boeing Revisits Morgantown," *Transit Pulse*, Vol. XIII, No. 5, January/February 1996.

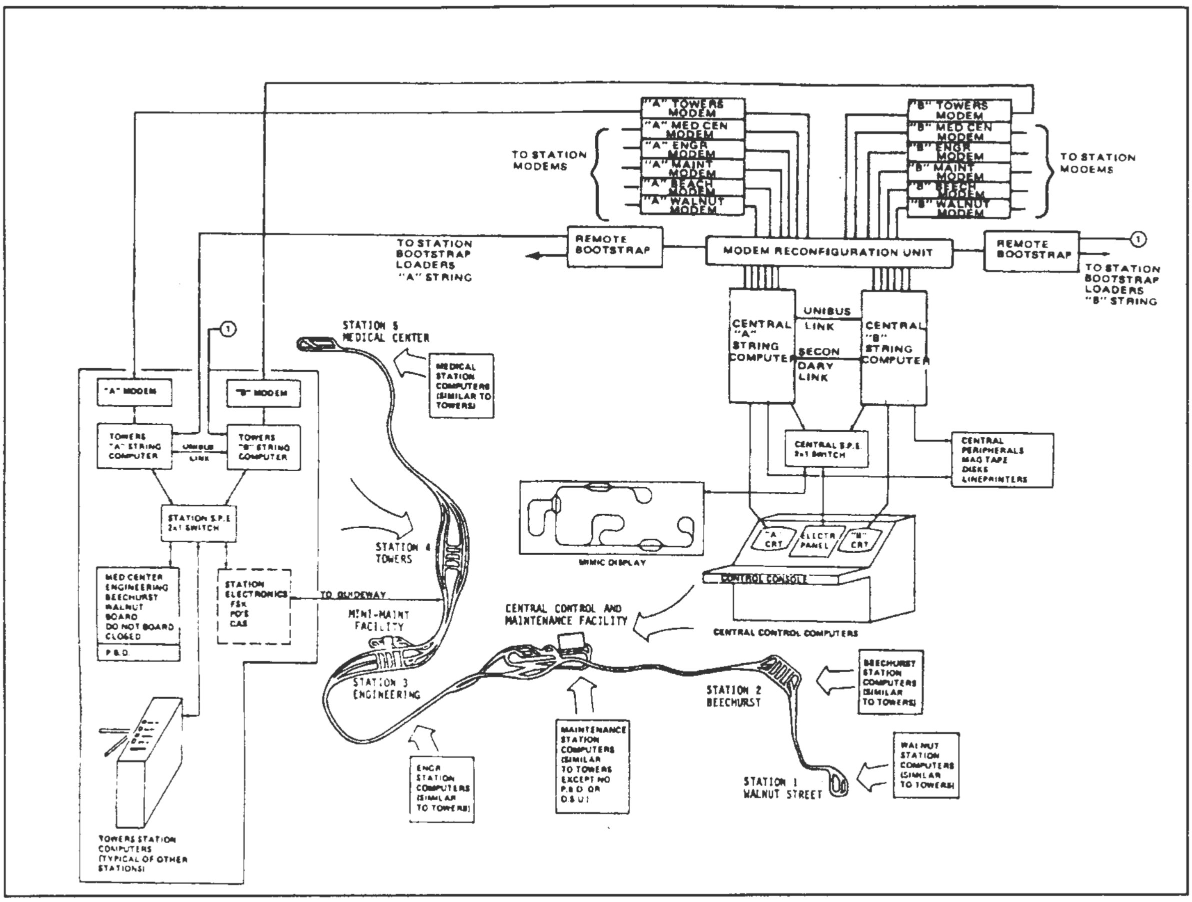


Figure 1. M-PRT Phase II Redundant Computing System

The operational software controls the system configuration, manages the movement of vehicles and passengers between stations, controls the movement of vehicles on the guideway and in the stations, and provides control and display capabilities for the operators at the central control complex. It consists of a custom executive, central applications program (CAP), passenger station applications program (PSAP), and maintenance station applications program (MSAP.) These applications programs perform the functions that control system operation from the passenger and operator point of view. The executive program controls the processing performed by the applications programs, provides the software interface with the computing system and external environment, and controls the configuration of the operational resources. The software was programmed in PDP 11 assembly language, except for 1360 lines of FORTRAN.

The Control and Communications System (C&CS) provides the link between computers and software to the guideway, stations, central control and the vehicle. The components of the C&CS are: Guideway Control and Communications System (GCCS), Station Control and Communications System (SCCS), Central Control and Communications System (CCCS), and Vehicle Control and Communications System (VCCS). The present system makes use of modem communications between the stations and central control and inductive communications between the guideway and the vehicle. The station electronics, which interfaces with the guideway communications, also interfaces with the station computers.

Additional background information is available in references 1 and 2.

2. COMPUTER PROBLEM DEFINITION

2.1 Site Survey

The first task in the study was to define the current and potential computer problems and assess their impacts. To find out about the state of the existing system, Boeing engineers Bert Hill and Paul Weis traveled to West Virginia University. On November 28 and 29, 1995 they met with Bob Bates (Director - Transportation and Mail Service), Bob Hendershot (PRT Systems Engineering Manager), and Jim Hatcher (responsible for PRT computers and software).

Primary topics discussed with the WVU personnel included:

- System performance experienced over the last 20 years and what has been needed to keep it operating.
- Computer failures and the resulting impact to operations
- Options available to rehost the existing software, including:
  - Emulation of existing PDP11 code
  - Recoding of the existing software into the language of a new platform
  - Use of an off-the-shelf Executive
  - Use of a higher-order language for user code (C, Ada)
- Specific issues the university thought should be considered while the upgrade is accomplished.
- Possible simplifications to the computer system in light of present day reliability and performance.

The survey also included a trip on the PRT.

Over the years, the MPRT has become an essential element of the transportation infrastructure in the Morgantown area and is the primary means of student transit between the geographically separated WVU campus areas. As such, the MPRT carries 2 million passengers per year. Measured system availability is consistently in the 99% range, significantly exceeding other transit modes such as rapid rail. However, availability has been degrading as system elements, in particular the computer system, have aged. Over time, WVU has upgraded many of the M-PRT system's non-computer sub-systems to enable them to keep operating for the next 15 to 20 years. However, other than replacement of the operator terminals, there have not been any upgrades to the computer subsystem.

2.2 Computer Failures

A critical situation exists today as far as computer maintenance is concerned. Digital Equipment Corporation (DEC) currently maintains the computers and Special Purpose Equipment (SPE) but has indicated that they are not willing to continue this service beyond July 1, 1997. The most common failures are computer system boards (i.e. memory, disk system, etc.), which, because of the redundancy scheme, can be repaired before any downtime results. The largest impact to system operation has come from SPE failures. Though less frequent, these failures involve one-of-a-kind special purpose DEC modules. Spare boards are very difficult to replace or repair since most of the failures require replacement of specific chips on the boards. A majority of these chips are no longer in production and are difficult to obtain. The station electronics are not a reliability or maintainability issue and these will not be part of the upgrade.

2.3 Software Rehost

WVU stated that PDP emulation hardware, which is commercially available to replace aging PDP11 equipment, is not a desirable option. While this emulation hardware would allow PDP11 code to run on modern personal computers (PCs), it would not solve the SPE maintenance problem. In addition, since the software would still be written in PDP-11 assembly language, emulation would be a short-term solution and would not allow the University to make other system improvements. Therefore, rehosting the existing software using an off-the-shelf operating system for the executive and a high order language for the applications code is the University's desired approach.

2.4 Issues

- WVU would like the DSU and boarding displays to be removed from the SPE to eliminate a major nuisance cause of switchovers. According to MPRT operations personnel, non-critical items hardware such as the Destination Select Unit (DSU) cause the most SPE reconfiguration (switchover) requests. Investigation usually shows that the switchover was initiated as a result of a malfunction in the input multiplexer operation, rather than a hardware failure. The only maintenance action required is a computer restart to put failed string back into operation.

- As part of the computer upgrade, standard interfaces for all devices should be used. The synchronous modems are the largest user of computer throughput and should be upgraded (they are a low 2400 baud, and each character transmission generates an interrupt to the CPU). The tape and disk peripherals are obsolete and components for the devices are difficult to procure.

- Magnetic media source code was not provided for the existing system. The MPRT computer software maintenance engineer has generated source files but most of them have not been verified to be correct.

- The Mimic Board is necessary for operations and there was no expressed desire for any changes.

- WVU would like to use commercially available programmable boarding displays at the stations. This would required a change to the existing computer/display interface and the software that drives the boarding displays. The operators would like to create boarding display messages through operator entry of ASCII characters.

2.5 Simplifications

- A 'cold' spare computer would be considered as part of the upgrade, as long as restart was automatic, safe, and timely.

- WVU would like all peripherals to use standard interfaces (Ethernet, SCSI, etc.). They would also like common SPE to be used at all stations. The operators presently use a console type printer (DECwriter) for event recording. The line printer delivered with the existing system was not required for operations and does not need to be included in the upgrade.

2.6 Other

- Choosing a low cost solution is extremely important since funding the upgrade will be a challenge.
- The capability for single station prime-to-backup computer reconfiguration is a major desire.
- While summer quarter would be the best time of year to perform the upgrade, other times of the year are also acceptable. WVU mentioned that the Towers and Medical stations could be removed from the system in order to provide system verification testing for the upgrade.

2.7 Conclusion

M-PRT/WVU personnel repeatedly expressed their desire to use "standard interfaces" in the computer upgrade. These standard interfaces will maximize the flexibility available to the university and DOT when selecting equipment and vendors.

3. ALTERNATIVES DEFINITION

The primary options identified for this study are (1) upgrading the existing computer system and rehosting the software and (2) implementing a newer technology control system. In sections 3.1 and 3.2 we look at alternatives for the computer platform and real-time operating system upgrades, and in section 3.3 we identify new control system technologies that could be applied to M-PRT.

3.1 Computing Platform Architecture Alternatives

3.1.1 Candidate Architectures

There are many computing platform architectures available that are capable of performing the functions required by the M-PRT. In order to provide a more in-depth analysis of those platforms that have the best chance of being selected, we performed an initial screening to eliminate several candidates from consideration. Table 1 lists the initial candidates that we considered.

Number	Candidate
#1	X86 architecture (Intel, etc.)
#2	68XXX architecture (Motorola, etc.)
#3	PowerPC architecture (IBM, Motorola, etc.)
#4	Alpha (Digital Equipment Corporation)
#5	MicroVAX (Digital Equipment Corporation)
#6	PDP 11 Emulation (Strobe Data Inc.)
#7	SPARC (Cypress, etc.)
#8	MIPS (IDT, etc.)

Table 1. Initial Candidate Platforms

After identifying the candidates, we defined a set of initial screening criteria, shown in table 2.

	Criteria	Rating System
1	Number of Sources	Single (S), Multiple (M)
2	Projected Life Cycle	Long (L), Medium (M), Short (S)
3	Risk	Low (L), Medium (M), High (H)
4	Life Cycle Cost	Low (L), Medium (M), High (H)

Table 2. Screening Criteria

We applied these criteria to the list of candidates, as shown in table 3. Since the intent of the study is to recommend a computer platform that will be available for the next 15 to 20 years, candidates #5 and #6 can be eliminated using screening criteria #2 (projected life cycle). It is unlikely that these two candidates will be viable for many more years. Candidates #4, #7, and #8 can be eliminated because of their high risk and projected high life cycle cost. Candidates #1 (X86) and #2 (68XXX) are the most widely used platforms today, and likely will be for many more years. These two candidates, along with candidate #3 (PowerPC), will be considered in depth during the detailed analysis phase of the study which will expand the evaluation criteria.

	Candidate Platform							
Criteria	#1	#2	#3	#4	#5	#6	#7	#8
Sources	M	M	M	S	S	S	M	M
Life Cycle	L	L	M	M	S	S	M	M
Risk	L	L	M	H	H	H	H	H
Life Cycle Cost	L	L	M	H	H	H	H	H

Table 3. Initial Candidate Computer Platform Screening

3.1.2 Hot Backup Capability

The capability for a hot backup is primarily dependent upon the operating system selected. Each of the candidate computer platforms selected for further analysis can support a system operating with a hot backup.

3.1.3 Special Purpose Equipment (SPE) Replacement Alternatives

Several alternatives exist for replacing the Special Purpose Equipment (SPE) that is part of the current M-PRT computer system. Likely alternatives include custom designs based upon the existing SPE. Off-the-shelf programmable logic devices (Xilinx, gate arrays, etc.) will most likely be used to replace the logic functions of the existing SPE. The interface between the Station Electronics and the SPE would be very similar to what is used in the system now, to avoid modification of the station electronics. The interface between the SPE and the computer system (currently performed by DR11A/C) would be replaced by a currently available industry standard interface. Alternatives include: Ethernet, SCSI, Centronics, GPIB, and RS-485. An additional alternative would be no SPE at all, given that reliability requirements could still be met. Each of these alternatives will be considered in greater detail during the analysis phase of this study.

3.2 Commercial Operating System Alternatives

The objective of the commercial operating system alternatives evaluation is to identify an off-the-shelf product that can perform the functions of the existing M-PRT Executive software. This software, summarized in figure 2 performs application software management, input/output (I/O), and system configuration management.

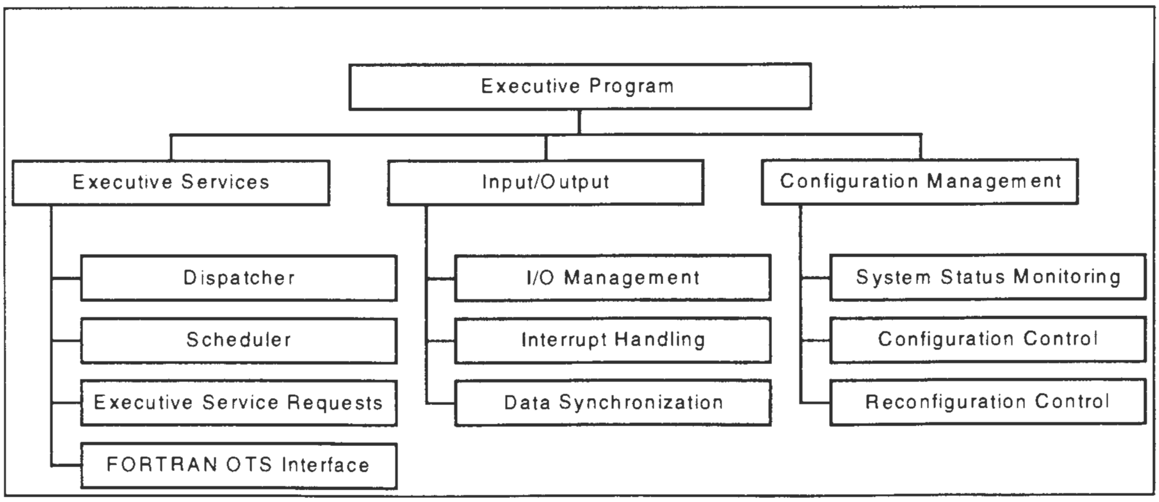


Figure 2. M-PRT Executive Software Top Level Structure

Commercially available real-time operating systems contain several features that perform some of the functions of the Executive software:

- Scheduling: modern systems usually provide both fixed and dynamic priority scheduling capabilities. Fixed priority scheduling is sufficient for M-PRT.
- Intertask communications and intertask synchronization: These capabilities are required to support redundancy management.

- Remote monitoring: this function would be used to allow the prime and backup computers to monitor each other (both central and station) and for the central computers to monitor the stations.
- High order language interface: all of the real-time operating systems come with C utilities and run-time libraries. Many also come with C++ and Ada support.

Performance requirements were met using the PDP-11 systems and are not anticipated to be a driving factor in the upgrade:

- Switchovers and seize controls must be completed within 500 milliseconds after a failure that could interfere with system operation occurs.
- Data synchronization must not require the backup to be disarmed for more than 10 seconds.

We performed a literature search and found a large number of commercially available real-time operating systems with versions for at least two of the three hardware platform alternatives. Nine of the most well-known of these operating systems are listed in Table 4.

Operating System	Vendor
Nucleus Plus	Accelerated Technology, Inc.
pSOS+	Integrated Systems, Inc.
Precise MQX	Intermetrics Microsystems Software, Inc.
LynxOS	Lynx Real-Time Systems
VRTX32	Microtec Research, Inc.
OS-9	Microware Systems Corporation
QNX 4.22	QNX Software Systems Ltd.
RTMX	RTMX, Inc.
VxWorks	Wind River Systems Inc.

Table 4. Commercially Available Real-Time Operating Systems

To narrow the list of alternatives to be used in the detailed alternatives evaluation, we looked at attributes that are not essential but are highly desirable for the M-PRT operating system

- Supports diskless systems (ROMable)
- Supports remote monitoring and debugging
- Provides features to simplify implementation of hot backup
- Source code available
- Integrated development tool set for development and maintenance. Both C and Ada compilers should be supported. In particular, the tool set should run on a PC so that the M-PRT will not need a UNIX workstation to perform software maintenance.

Since QNX and RTMX only have UNIX development platforms, we eliminated them from further consideration. Nucleus has remote monitoring but not remote debugging so it was eliminated. Source code is available for all of the candidate systems and all are ROMable. An understanding of features that support implementation of hot backup requires more detailed analysis. Therefore, we recommend proceeding with detailed evaluation for the six remaining operating systems.

3.3 New Technologies Alternatives

3.3.1 Existing Systems Technology

We contacted nine existing automated transportation system operators including Automated Guideway Transit (AGT) systems and properties that employ Automatic Train Control (ATC) operations. The intent was to obtain information on the present state of technology being used for computer systems and control systems. The analysis done in section 4.3.1 then uses this information to determine if there are any particular technologies that may be applicable to M-PRT with the objective of enhancing operations and maintenance.

The following paragraphs describe a specific transit system approach to operations with respect to:

- Present computer system and control system being used
- Single or dual string system
- Service contract or self maintenance
- Operating system
- Architecture

O'Hare Airport Transit System. The computer and control system used for the O'Hare Transit system is maintained by the French firm, MATRA, (the O'Hare system was furnished and deployed by MATRA). The automatic train control computer is a MATRA design. The central supervisory computer consists of redundant DEC MicroVAX's. They run a prime computer which is switched to the backup when a problem is detected in the prime. All software is MATRA design.

SeaTac Airport Transit System. SeaTac uses a single Hewlett-Packard HP1000 computer for transit supervisory (central) functions only . The Westinghouse Company (WECO) train control has a separate computer system which operates independently. SeaTac originally had a WECO computer for the central application which became obsolete and the HP1000 was installed. The HP is also reaching the end of its useful life. They have a service contract with Hewlett Packard. When the HP was installed the WECO software was rehosted. The software is written in FORTRAN.

New Denver International Airport Automated Ground Transportation System. The Denver Airport Systems uses the same AEG Transportation Systems (WECO) technology as is used on all similar airport transportation systems - Denver did not do anything out of the ordinary. The computers used are proprietary to AEG. Maintenance is done under service contract by AEG.

Dallas/Fort Worth AirTrans System. AirTrans was deployed at roughly the same time as the Morgantown M-PRT and has similar operating experience. The AirTrans operations group has done a number of computer upgrades but has always used the same computer manufacturer, Modular Computer Systems (ModComp), of Fort Lauderdale, FL. Since the early 1970's, the central computer has been through two (2) upgrades and the station computers through one (1) upgrade. AirTrans has done studies similar to the M-PRT study for their central computer. The AirTrans software was originally written in assembly language like M-PRT. AirTrans looked at going to a higher order language (C++), but did not do this for technical reasons. Their AirTrans control system allows operations without the central computer in the loop. (Vehicle/guideway control and safety is provided by a General Railway Signal (GRS) control system, central is used as a supervisory, non-critical function). Central operations employs a prime central computer with a cold backup. switchover from prime to backup requires some manual operations. Over the years AirTrans has looked at going to a new computer system. They've looked at IBM, DEC, HP and most of the other major manufacturers, but found that ModComp gave them the most for their money. ModComp uses a real time UNIX package and their own in-house executive.

Miami Metromover. This is an AEG/Westinghouse system. The AEG/Westinghouse software has been rehosted once and now runs on Intel 486 computers. Operational experience is similar to SeaTac and the New Denver Airport.

Bay Area Rapid Transit (BART). BART is in the process of changing their Central supervisory computers to Tandem triplex computers. BART uses a voting process for determining the health of the Central computers and they take advantage of the Tandem fault management capabilities. The computer capabilities at the station are part of the Automatic Train Control (ATC) system and are separate. BART has used a number of ATC systems over the years. BART is presently testing a communication-based Advanced Automated Train Control (AATC) system. This system is further discussed in sections 3.3.2 and 4.3.2.

San Francisco MUNI. San Francisco MUNI is presently in a major upgrade of their operational system. They are in the process of completing the design portion of the program to implement an Alcatel communication-based control system. The new system will control the subway portion of the MUNI system. MUNI is unique in that it requires both automated and manual control. The new communication medium is radio frequency (RF) based. The system design is similar to Vancouver SkyTrain, even though the communication medium is changed (see below). They have a smart wayside and a semi-intelligent vehicle. The Central computer is triplex for vital functions, they have dual computers in the station. Central also has supervisory functions. The computer system is IBM PS-2 based. The fault management and control software is Alcatel proprietary.

Vancouver SkyTrain. The Vancouver SkyTrain uses the Alcatel communications-based train control. Wayside/vehicle communications are done by means of leaky coax transmission. The wayside computers are triple redundant IBM PC's which use a 486 operating system. The system was upgraded to IBM's from Data Automation computers a few years back. At the time of the upgrade the software was rehosted. The Central computer is single tread and is used for supervisory functions only. The Central computer is IBM/486. Alcatel provides service for the system.

Washington, D.C. Metro (WMATA). Washington Metro is a large automated rail system that originally used PDP11 technology. Over the years the computers have been upgraded but the overall system has remained DEC and VMS oriented. At the track and central supervisory level the systems are redundant. The central supervisory functions use Jupiter equipment, at the track control level the equipment is DEC Alpha. The Alpha equipment gives them the flexibility to run VMS, UNIX and Windows. The train control system has been upgraded over the years and as a result is a mixture of American suppliers. Washington Metro uses service contracts for computer maintenance, they do not recommend doing this kind of maintenance in-house.

3.3.2 Communication - Based Control Technology

In order to determine the suppliers and status of communication-based systems development, we conducted a search of industry literature. This search identified suppliers of train or transit control technology who are actively pursuing this market in either the U.S. or Canada. We then obtained additional information as to the status of their products in order to determine if their control technology could be applied to M-PRT. This approach does not preclude international suppliers since a number of these suppliers are pursuing North American business and have U.S. operating divisions. We also investigated the applicability of other communication-based control technologies that possibly could be used to enhance M-PRT operations and maintenance.

Passenger Carrying Operations. Our literature search for potential Communication-based Control Technology commercial (or industry) suppliers turned up the following list of suppliers who have systems, or are developing systems, for United States or Canada passenger carrying operations. The list is based on rail industry literature search and data obtained from De Leuw, Cather & Company study: New Technology Signal System Study; done for MTA, New York City Transit, dated October 5, 1994.

- ABB Signal
- Alcatel Transport Automation
- General Railway Signal
- HMK (BART)
- Safetran Systems
- Union Switch and Signal
- AEG Transportation Systems
- GEC Alsthom Signarail
- Harmon Industries
- MATRA
- Siemens Transportation Systems

On March 16, 1995, Daimler Benz announced the merger of rail activities between ABB Asea Brown Boveri Ltd and AEG Daimler-Benz Industrie forming ABB Daimler-Benz Transportation. While ABB Signal had developed a system known as EBICAB850R for demonstration, it may not be supported by the joint venture and is not included in this evaluation.

Freight System Applications. We found two communication-based control systems designed for freight and long-haul passenger applications. The Burlington Northern/Union Pacific (BN/UP) freight Positive Train Separation (PTS) Project being developed by GE - Harris Railway Electronics. Harmon Industries is developing a similar system for Amtrak. The Harmon system is called Incremental Train Control System (ITCS). Harmon is also developing a communication-based moving block control system called Ultrablock™ for transit applications.

Although PTS and ITCS are examples of communication-based control, neither is presently applicable to transit moving block technology

Other International Suppliers. We found two international communications-based system suppliers, CMW (Sao Paulo, Brazil), and Westinghouse Signals Ltd (London Underground). Both of these suppliers have been merged with companies which are part of the list to be considered. These international suppliers will not be considered separately.

We contacted each of the active suppliers identified in the literature search to obtain information about their system applications and product lines. Table 5 summarizes the results of this survey.

As noted in the table, a number of these new systems will be demonstrated for the Toronto Transit Commission (TTC) in 1996.

Supplier and Application	Product Line
ABB Daimler-Benz Transportation Systems. Toronto Transit Commission (TTC) 1996 demonstration of advanced technology communications-based train control systems	**AEG Flexiblok™**. Uses spread spectrum radio communications. Distributed, vehicle oriented system in which trains calculate their own movement. Utilizes central control for system optimization and for communications over a wayside network of regional ATC computers, which control interlocking and other wayside vital and non-vital equipment for system safety and operation. Each region communicates with trains over a base station radio, which can use either a point-source or distributed antenna. A "virtual occupancy" is calculated to determine a safe stopping distance using existing techniques developed for fixed-block systems. This information is compared to "conflict point" information to determine safe train spacing. Conflict points can be misaligned routes, switches, station stops, grade crossings, or the train ahead. Passive devices at known fixed locations called "norming points" are used to correct any positioning error and to update an onboard system map.
Alcatel Transport Automation. San Francisco MUNI, in design; Vancouver SkyTrain, in operation; Ankara, Turkey, being deployed.	**SELTRAC®**. Uses inductive and radio communications. Capable of fully automatic train control. Ankara application uses an inductive loop to provide continuous, two way, high capacity train/wayside communication, train detection and train position. Because of the accuracy of the vehicle position the control system is able to employ moving-block principles which allow trains to operate within a safe braking distance of the last verified position of a preceding train.
GEC Alsthom Transport. Toronto Transit Commission 1996 demonstration of advanced technology communications-based train control systems.	**SACEM New Generation**. Communications-based virtual block version of the train control system in use on the Paris RER regional rail system. Continuous track/train transmission via the rail, inductive cable, spread-spectrum radio or wave guide. For train location SACEM uses phonic wheels which are equivalent to a tachometer, communicating with wayside beacons. Toronto application will use frequency - hopping spread-spectrum radio communications, and fixed blocks of 25 meters or greater. Wayside equipment consists of a sector computer and maintenance terminal, and radio base stations. Onboard equipment consists of a SACEM train-borne computer, radio antenna, phonic wheels, beacon sensors, and the Visucab operator's display.
General Railway Signal. Toronto Transit Commission 1996 demonstration of advanced technology communication-based train control systems.	**ATLAS™**. Uses a frequency-hopping spread-spectrum radio for train-wayside communications. System features distributed vital wayside control sectors, intelligent vehicles, variable blocks, and train location using beacons for location re calibration. System safety is independent of the communications channel. Vehicles in the ATLAS™ system are equipped with two vital databases. An infrastructure data base handles civil speed limits, grades, switch locations, station stop points. platform doors, control sector limits, beacon locations and identifications, communication zone locations, and spread-spectrum codes. A vehicle parameter data base handles service brake rate, brake switch time, grade build-up time, tachometer scale factor, default train length, acceleration rate, and wheel size change. The system can accommodate a range of vehicle to wayside communications mode which include leaky coax and fiber optics. Will offer open architecture protocols.

Table 5. Communications - Based Technology Products (continued next page)

Supplier and Application	Product Line
Harmon Industries. Toronto Transit Commission 1996 demonstration of advanced technology communications-based train control systems.	**UltraBlock™**. Provides continuous communication of dynamic train data between wayside and trains via data radio. Subsystems include onboard controllers, and wayside controllers with interfaces to interlocking controllers. Onboard equipment determines train location using fixed wayside transponders as reference markers. Onboard readers detect these transponders and combine this information with odometer-measured distances and a digitized system map. Onboard equipment evaluates train location, speed, movement authorization, and the system map to calculate and enforce safe operating speeds. Interlocking control equipment can either replace existing equipment, or interface to it, thus allowing overlay capability.
HMK (Hughes and Morrison Knudsen). Bay Area Rapid Transit (BART) **Advanced Automatic Train Control (AATC)** system, presently in test.	Combination of the Hughes Enhanced Position Location Reporting System (EPLRS) with Morrison Knudsen microprocessor-based train control. Uses spread-spectrum radio technology for communications. Designed for continuous positive train separation management with positive reinforcement. High resolution position determination and reliable transfer of command information is achieved both in and out of tunnels using spread spectrum radios placed at quarter mile to one mile intervals. Radios on board trains communicate in time multiplexed fashion with radios placed along the tracks. Information received by the wayside radios are relayed by radio to the station computer where train position is determined based on radio frequency (RF) propagation time between train and wayside radios. Train motion commands are then determined in the station and relayed back to the trains to enforce train movement. The test system is designed to be overlaid on the existing track circuits.
MATRA Transport. Maggaly System - in operation.	**SACEM(Maggaly).** A continuous speed control system with moving block control. Contains two components that are applied to communications-based train control: axle-mounted "phonic wheels for speed measurement" which communicate with wayside RF beacons to calibrate distance and receive operational information; and an intelligent vehicle which carries system map data necessary for dynamic analysis and speed control.
Safetran Systems. Component Development	Incremental Train Control System (ITCS) project development. **S3/Link™ Spread Spectrum Radios**, units can be arranged to form point-to-point or point-to-multipoint networks. Developments under way include a complete radio-based signaling system to replace wayside signal controls; both intermediate signal control modules and complete modular interlocking are being developed as a part of **Geo/Link™**. "The final goal is to provide a complete radio-based wayside signal system which can be upgraded to a cab signal and train control system by incrementally installing PTS/ATCS MCP radios and vital onboard computers in locomotives. At this point, a vital office computer can be installed, full vital PTS/ATCS specification train control turned on, and wayside signals removed."
Siemens Transportation System. Development based on Dortmund, Germany People Mover, which is in operation.	Moving-block signaling development based on people mover experience. Development activities are coupling this experience with modem communications links.

Table 5. Communications - Based Technology Products (continued next page)

Supplier and Application	Product Line
Union Switch and Signal. Developing system based on Los Angeles Green Line experience, which is in operation.	**MicroBlok™** train control system. Designed as close as possible to a traditional (track- circuit-based) signaling system. Uses the concept of "virtual" blocks, which can be of any length required. The virtual track circuit logic determines what profile data can be transmitted to the vehicle, depending on the number of circuits occupied. Vehicle/wayside communications employ a data radio using "leaky" coaxial cable and antennas on the vehicle. Communications are bi-directional, and route data transmitted from the wayside to the vehicle can be encoded to take many forms (switch position, line speed, target speed, distance to go). Wayside data beacons are strategically located at entrances and exits of interlocking zones called "communications zones." these passive beacons transmit data to the vehicle, and are capable of retaining ATO and ATP information a well as topographic information. Vehicle positioning can be determined through a system known as TIPS (train inertial positioning system). TIPS works in concert with the wayside beacons, which update the "roaming error" associated with an inertial guidance system. Vehicles are intelligent, and can keep track of their location. Vehicles are programmed to know beacon locations, the track plan, normal civil speeds, and switch locations. Civil speed restrictions can be encoded. In conjunction with TIPS, vehicles generate their own profile calculations. Vital logic is distributed on the wayside and works in concert with a non-vital central supervisory function.
GE - Harris Railway Electronics. Burlington Northern/Union Pacific **Positive Train Separation (PTS)** project	PTS is designed as an enforcement mechanism overlaid on the existing signal system. Uses RF communication links to deliver movement authorities to trains, deliver occupancy authority to maintenance/work crews, and return position reports to a central computer. PTS is meant to improve existing levels of safety by insuring that signals are obeyed before a violation occurs and by enforcing speed limits
Westinghouse Signals Ltd. London Underground, Jubilee Line, radio based wayside portion, test system	Is now part of AEG
CMW. Sao Paulo, Brazil, communication-based signal control system deployment	Is now part of GEC Alsthom

Table 5. Communications - Based Technology Products

Other Applicable Technology. The nature of communication-based control systems, centralized control and decentralized execution, provides many possibilities for obtaining M-PRT solutions from other than traditional sources. What has to be recognized is that the rigid safety standards applicable to transit or people-moving have to be inherent to any new control system. There is one technology identified as meeting these safety constraints: the Odometer Data Downlink Collision Avoidance System (ODDCAS). This technology was developed and demonstrated in the laboratory by the Boeing Company as part of the Advanced Group Rapid Transit (AGRT) program. It is a short headway, moving block, command, control and communication (C^3) system that used the M-PRT technology as a baseline but is applicable to train control. The AGRT C^3 system decentralizes control functions so the vehicle control is delegated to the local level; central performs only the supervisory functions that do not interact with the vehicle in real time.

The ODDCAS uses on-board odometer data to monitor vehicle speed and position throughout the route. Using an inductive communication link, vehicles report their speed and position periodically to dual wayside processors that compute separation between vehicles. Inadequate separation results in a command from the wayside processors to interrupt the "Safe-to-Proceed" signal. The dual processors are disparity checked for safety. The safety logic is continually exercised to immediately detect processor failures. The failure detection and reaction are fail-safe. Onboard the vehicle, dual processors with exercised software guarantee the integrity of the transmitted speed and position data.

3.3.3 Alternatives with Potential Application to M-PRT

We used the following criteria to select communication-based control technologies to be included in the study analysis (Section 4.3.2) for potential future application to M-PRT.

a. Technology is used in a system that is in operation, being deployed, being demonstrated, in test, or scheduled to be demonstrated.

b. Development is being performed by a recognized supplier which has published the concept of their system design.

c. Technology implements transit moving block control.

Table 6 summarizes the status of the systems with respect to the screening criteria.

Vendor	System	Status
ABB Daimler-Benz Transportation Systems	Flexiblok™	To be Demonstrated - TTC 1996
Alcatel Transport Automation	SELTRAC®	San Francisco MUNI - in design 1996/97 Vancouver Sky Train - in operation since 1986 Ankara, Turkey - being deployed 1997
GEC Alsthom	SACEM New Generation	To be Demonstrated - TTC 1996
General Railway Signal	ATLAS™	To be Demonstrated - TTC 1996
Harmon Industries	UltraBlok™	To be Demonstrated - TTC 1996
HMK	AATC	Bay Area Rapid Transit (BART) - In Test 1995/96
MATRA	SACEM	Maggaly - In operation since 1992
Safetran Systems		Presently Component Development only
Siemens		Dortmund, Germany - In operation, future development will be based on system experience, do not have a published system concept
Union Switch and Signal	MicroBlok™	In Development - System Concept Published
GE - Harris Railway Electronics	Positive Train Separation (PTS)	BN/UP PTS Project - In test. System is applicable to freight operations and not transit
Boeing Defense & Space Group	ODDCAS	Advanced Group Rapid Transit (AGRT) Control System - Demonstrated in Laboratory 1986

Table 6. Summary Status of Alternative Systems

3.3.4 Alternatives Selection

Based on the stated criteria, we eliminated three technologies from further consideration: Safetran, because they are presently doing only component development, and have not published a systems approach. Siemens, because they do not have a published system approach. GE - Harris Railway Electronics, because PTS is not a transit moving block technology. The remaining nine technologies will be analyzed in greater detail (See section 4.3.2).

4.0 ALTERNATIVES ANALYSIS

4.1 Computer Architecture

The computer architecture evaluation included a trade-off to determine the best computer hardware platform, a solution for replacing the existing special purpose equipment (SPE), and a look at integration of programmable boarding displays into the system. Figure 3 depicts our top level concept for the upgraded computer control system architecture. This architecture is much less complex than the existing system, having been reduced from two complete strings to dual central computers communicating with a single computer at each station. This simplification is possible due to the increased reliability of computing equipment and the wider range of commercially available interface devices.

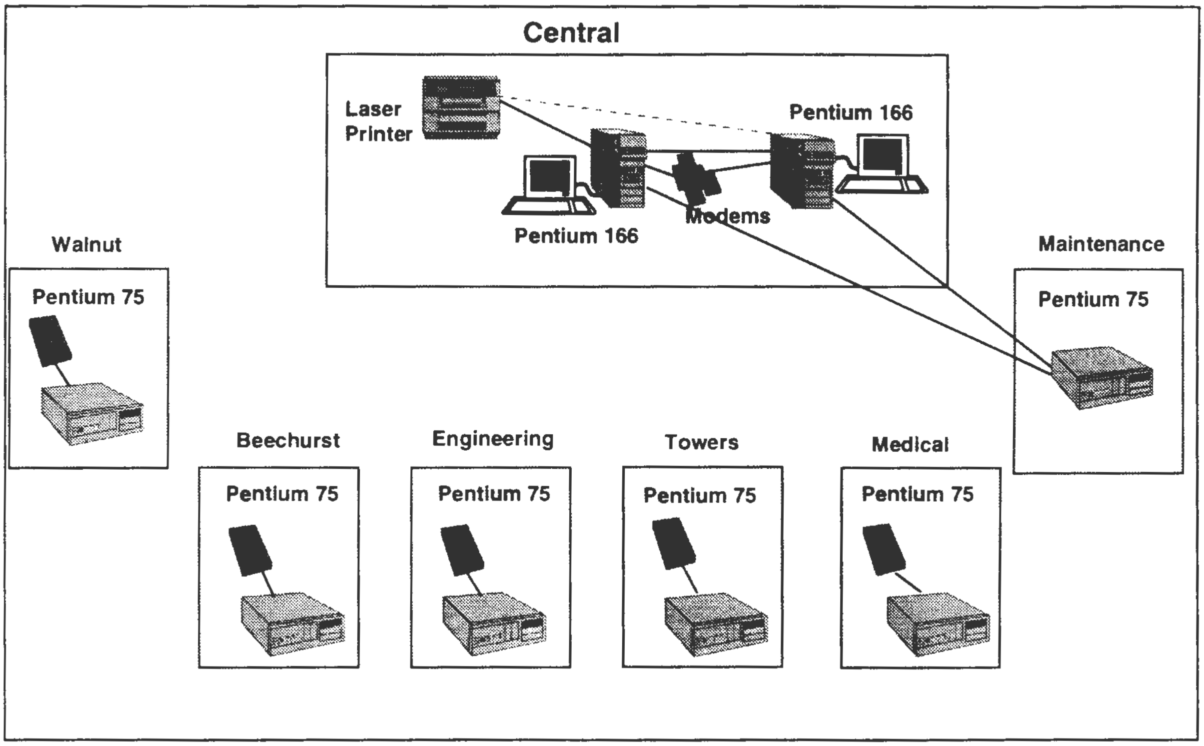


Figure 3. System Architecture Concept

Recommendation. The X86 computer architecture platform (specifically, a Pentium processor), was selected as the most viable for the MPRT upgrade project. The details of how this conclusion was reached are outlined in Section 4.1.1. In performing the study, it became apparent that a new computer system could meet the existing MPRT reliability requirements without requiring dual station computers. The side benefit of switching to single station computers was the ability to eliminate the SPE as it exists today. In an upgraded system, off-the-shelf, programmable I/O modules can be used to directly interface to the Station Electronics. The only aspect of a new interface between new computers and the Station Electronics requiring unique design is the cabling. The proposed new architecture includes dual central computers, with the backup restricted to monitoring status while the prime is functioning correctly.

Reliability Assumptions. The reliability requirement allocated to the computers for the existing system is 175 hours mean time between failures (MTBF). Over the last six years (7/1/89 to 6/30/95), the actual reliability has averaged 310 hours. Starting with the least recent year-end figure (6/30/90) and proceeding to the most current (6/30/95), the respective yearly numbers were: 1221 hrs, 914 hrs, 279 hrs, 283 hrs, 175 hrs, and 212 hrs. With the architecture as proposed in Figure 3, it is expected that the reliability would be on the order of 2000 hrs or better. This value is derived using the following assumptions: MTBF of greater than 40,000 hrs for the basic station or central computer (processor card, power supply, backplane, and local memory); MTBF of between 21,000 hrs (Engineering) and 40,000 hrs (Walnut) for the required station I/O modules (serial ports, parallel ports, etc.); MTBF of 60,000 hrs for the required central I/O modules. The hard drive and floppy drive at central were not included in the calculation because they are not critical devices after system initialization. The MTBF estimates are based upon vendor published data.

4.1.1 Computer Hardware Platform Solution

To find the best solution for upgrading the computer hardware platform, we constructed a trade-off matrix containing the screened alternatives as shown in Table 7 and described below. The three computer platforms identified in Table 7 were arrived at during the initial alternatives identification phase described in Section 3.1 of this report.

Processor Manufacturers. This criteria directly affects the cost of the processor. Multiple processor manufacturers leads to greater competition and lower costs. Rankings are based upon the number of manufacturers (most manufacturers = highest rank).

System Vendors. This criteria is very similar to processor manufacturers in terms of evaluation. Once again, the more vendors, the greater likelihood of lower costs (and greater availability). Rankings are based upon the number of vendors (most vendors = highest rank).

Operating Systems. Are the operating systems which meet the MPRT requirements supported? Each platform is capable of supporting all of the operating systems being seriously considered. All platforms received the same rank of 1.

Interface Compatibility. The computer system must be compatible with the existing interfaces not being upgraded, specifically, the station electronics interfaces. For the interfaces being upgraded, does the primary computer have a standard interface? Can the interface hardware be purchased off-the-shelf? For each of the platforms considered, off-the-shelf hardware can be used to directly interface to the station electronics (assuming a switch to single-string at each station). For the x86 and PowerPC platforms, the interface hardware would be identical (PCI/ISA based peripheral cards), thus each receive the same rank (1). For the 68xxx, off-the-shelf interface hardware is also available, but with fewer vendors offering hardware with the proper bus type.

Reliability. Each computer platform being considered will meet the existing system specification reliability (MTBF) requirement of 175 hours. For each of the platforms being considered, the MTBF is expected to be greater than 2000 hours (assumes 6 single string stations and dual central configuration). MTBF estimates are based on vendor specifications for various single board computers and standard interface cards that could be used. The number and type of interfaces for each station and central were included in the estimate. The interface hardware used to communicate with the station electronics and other devices drives the reliability calculation, not the processor IC. For this reason, each platform scored a ranking of 1.

Maintainability. Because each platform would be housed in a PC style enclosure (tower or otherwise), with off-the-shelf processor and interface modules, maintenance should be easily accomplished. Card or computer swapping can be accomplished with minimal effort. Maintenance could be performed by MPRT personnel or vendor supplied. Each platform scored a ranking of 1.

Platform Processor	x86/Pentium		68xxx		PowerPC	
Processor Manufacturer(s)	Intel, Cyrix, Nexgen, AMD, etc.	1	Motorola, etc.	3	IBM, Motorola, etc.	2
System Vendors	Micron, HP, Compaq, Dell, IBM, DEC, etc.	1	Apple, Motorola, etc.	2	Apple, IBM, Motorola, etc.	2
Operating Systems	Lynx, OS-9, pSOS, VRTX32, VxWorks, Windows, etc.	1	Lynx, OS-9, pSOS, VRTX32, VxWorks, MacOS, etc.	1	Lynx, OS-9, pSOS, VRTX32, VxWorks, MacOS, etc.	1
Interface Compatibility	Off-the-Shelf interface cards, PCI/ISA bus	1	Off-the-Shelf interface cards	3	Off-the-Shelf interface cards, PCI/ISA bus	1
Reliability	exp MTBF >2000 hrs, interface hardware, not processor IC, dominates reliability	1	exp MTBF >2000 hrs, interface hardware, not processor IC, dominates reliability	1	exp MTBF >2000 hrs, interface hardware, not processor IC, dominates reliability	1
Maintainability	easily maintained (card or computer swap), self-maintenance or vendor supplied	1	easily maintained (card or computer swap), self-maintenance or vendor supplied	1	easily maintained (card or computer swap), self-maintenance or vendor supplied	1
Projected Life Cycle	born early 1980's, growing stronger, market dominance, no end in sight	1	born early 1980's, strong embedded systems market, limited new growth	2	born 1993, creating new niche market, sales increasing, new growth promising	2
Redundancy Management Features	software support only	1	software support only	1	software support only	1
Life Cycle Cost	fierce competition and large product volume continues to reduce cost	1	lower product volumes, prices more stable	2	lower product volumes, prices dropping slowly	3
Performance	198int/138fp SPEC92 @166Mhz (Pentium P54CS)	1	60int/45fp SPEC92 @50MHz (68060)	3	176int/157fp SPEC92 @133MHz (PowerPC 604)	1
Risk	low (mature platform, with extensive growth capability)	1	low (mature platform, but minimal growth capability)	3	low (new platform, but extensive growth capability)	2
Rank for all criteria	Average Rank = 1 Overall Rank = 1		Average Rank = 2 Overall Rank = 3		Average Rank = 1.5 Overall Rank = 2	

Table 7. Computing Platform Trade-Off Matrix (with relative rank)

Projected Life Cycle. Although it is difficult to predict the future of computer electronics, judgments can be made based upon past history and current expectations. Future obsolescence is reduced significantly by rehosting the software and converting to a high level language. From a hardware standpoint, the x86 instruction set architecture has been around since the early 1980's. Performance of the current Pentium processor (which is an extension of the x86 architecture) illustrates the commitment industry has shown to continue to support this architecture. With the extensive usage of this architecture throughout industry (as well as the personal computing market), it is highly likely to be supported for the long term (15-20 years) and thus receives a ranking of 1. The 68xxx architecture is similarly entrenched throughout industry (primarily for embedded systems and military applications), and is likely to also be supported for the necessary time frame. The 68xxx received a ranking of 2 because of the expectation that growth will be limited (Motorola is expected to push the PowerPC). The PowerPC is a new architecture (first shipped in 1993), but is quickly gaining support in industry. With both IBM and Motorola as chip vendors, it is likely to continue to be supported for the long term. The PowerPC received a ranking of 2.

Redundancy Management Features. With the elimination of the backup computers at the stations, redundancy management in the upgraded system becomes much simpler. At central, the two computers must continuously monitor each other and take appropriate action if one is found to have failed. In addition, the prime computer must keep the backup computer up-to-date every time a message is received or an operator command is entered. Since none of the candidate systems had these capabilities built into the hardware, each received the same ranking-- (1).

Life Cycle Cost. Volume of product and significant competition has reduced the cost of the Pentium grade computer significantly, as has the introduction of higher performance versions. Although the computer procurement cost is not going to be a significant portion of the MPRT system upgrade cost, it is not something that should be ignored. The x86 receives a ranking of 1 in this category primarily because of the sheer volume of system vendors, as well as current procurement prices. Maintenance costs and training costs are part of life cycle costs, and the x86 scores highest in these areas as well. The 68xxx receives a ranking of 2 because of stable prices (but with lower volumes and less competition). The PowerPC receives a ranking of 3 because of the cost of the systems using it, as well as the lower volume of product being shipped.

Performance. Each computer platform considered will meet the operational performance requirements. Still, because of some of the unknown aspects of the operating system to be chosen, relative performance can't be ignored. For the highest speed grades, the Pentium and PowerPC processors are almost equivalent (using SPEC92, which is an industry standard used to measure performance). Each of these were assigned a rank of 1. The 68xxx (of which the 68060 is the fastest) received a ranking of 3.

Risk. Risk should be low for each of the three computer platforms. Multiple vendors and manufacturers exist for each platform, and the architectures are expected to be supported for some time. On a relative basis, the x86 earns a ranking of 1 for its maturity, along with its growth potential. The PowerPC is a newer platform, but has significant growth capability and thus earns a ranking of 2. The 68xxx is a mature platform, but is expected to have limited growth and thus earns a ranking of 3.

Summary. Although any of the three platforms could perform the job adequately, the x86 architecture appears to be the best suited for the job and therefore is the recommended platform. Table 1 illustrates that the x86 architecture scored a ranking of 1, alone or tied, for each of the criteria considered. Weighting the criteria became unnecessary under these circumstances.

4.1.2 Interface to the Station Electronics

Since the high reliability of each of the platforms being considered removed the need for dual computers at the stations, we wanted to find a way to eliminate the SPE. We determined that off-the-shelf, plug-in modules (such as Industry Pack personality modules and carriers available from Greenspring Computers[2]) could be used to directly interface to the existing station electronics. Figure 4 shows the interfaces between the station computers and station electronics, as well as the other station computer interfaces.

For the DHU/DAU interface, as well as the DSU/Fare Gates interface, plug-in modules providing parallel, differential I/O (RS-422 electrical standards) can be used to communicate directly to the station electronics. Handshaking would be provided with software control, so as to avoid the need to change any aspects of the existing station electronics. The portion of this new interface that would not be off-the-shelf would be the cables, which would be very straightforward.

For the Collision Avoidance System (CAS) interface, plug-in modules providing open drain outputs would be used (replacing the existing open collector output drivers in the current system). Once again, new cables would need to be designed.

A standard serial port (RS-232) would be used to communicate to new boarding displays capable of receiving and displaying messages of various length and content. Boarding displays are discussed in greater detail in Section 4.1.3.

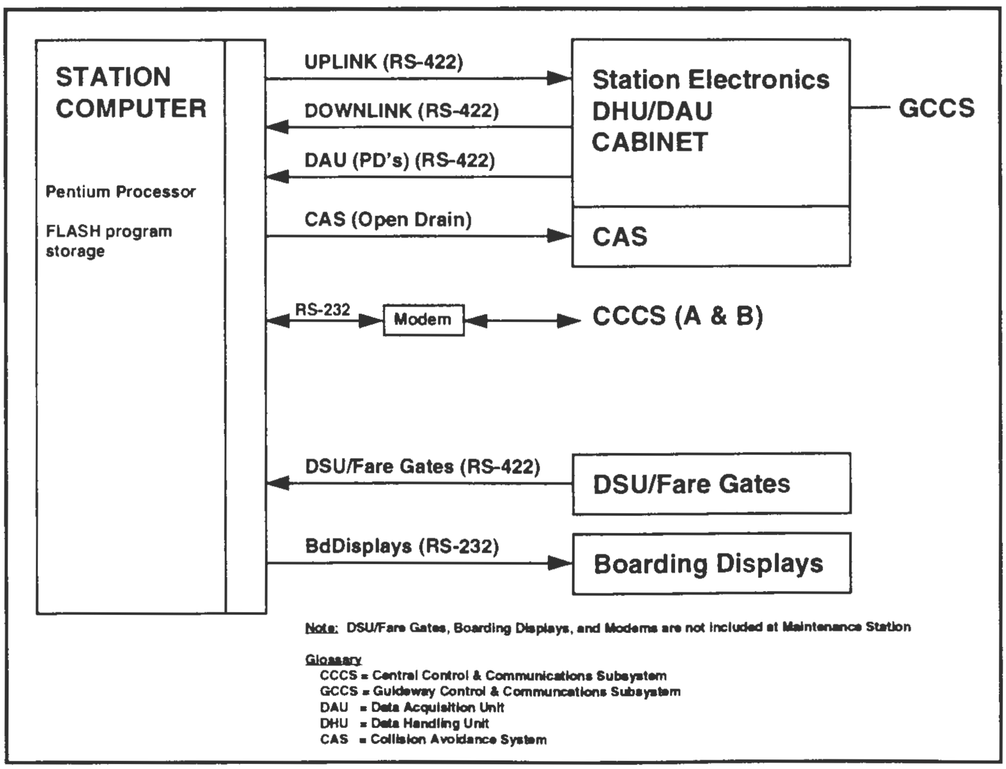


Figure 4. Station Computer Interfaces

---

2 Greenspring Computers (415) 327-1200
1204 O'Brien Drive
Menlo Park, CA 94025

4.1.3 Station to Central Communications

In our recommended configuration, station to central communications use off-the-shelf modem interface cards (RS-232 or RS-422), that connect to the existing modems. Each station has modem communication capability to each of the dual central computers, as shown in Figure 5. A digital share device (not shown) allows both central computers to connect to a single modem, if RS-232 is the electrical interface. If RS-422 is the electrical interface, it is possible to connect central A and B to the modems using shared lines, as characteristics of RS-422 allow multiple receivers on a line. Only one central computer would be allowed to send to the stations at any given time, regardless of which electrical interface is used. Because the maintenance station does not require a modem (due to its proximity to central), RS-422 would be the recommended electrical interface between it and central (to allow central A and B to share lines).

The existing station to central communications has been a significant system bottleneck. As explained in Section 2, the existing modems operate synchronously at 2400 baud. More significantly, each character transmission generates an interrupt to the computer. Various off-the-shelf modem interface cards are available with up to 32 byte FIFOs (for both transmit and receive), allowing an entire message to be transmitted with only a single interrupt to the computer. This provides the capability to significantly reduce the overhead associated with station-to-central communications, freeing up the computer for more important tasks. The new computer hardware could support rates up to 38.4K baud, with the rates being programmable by software.

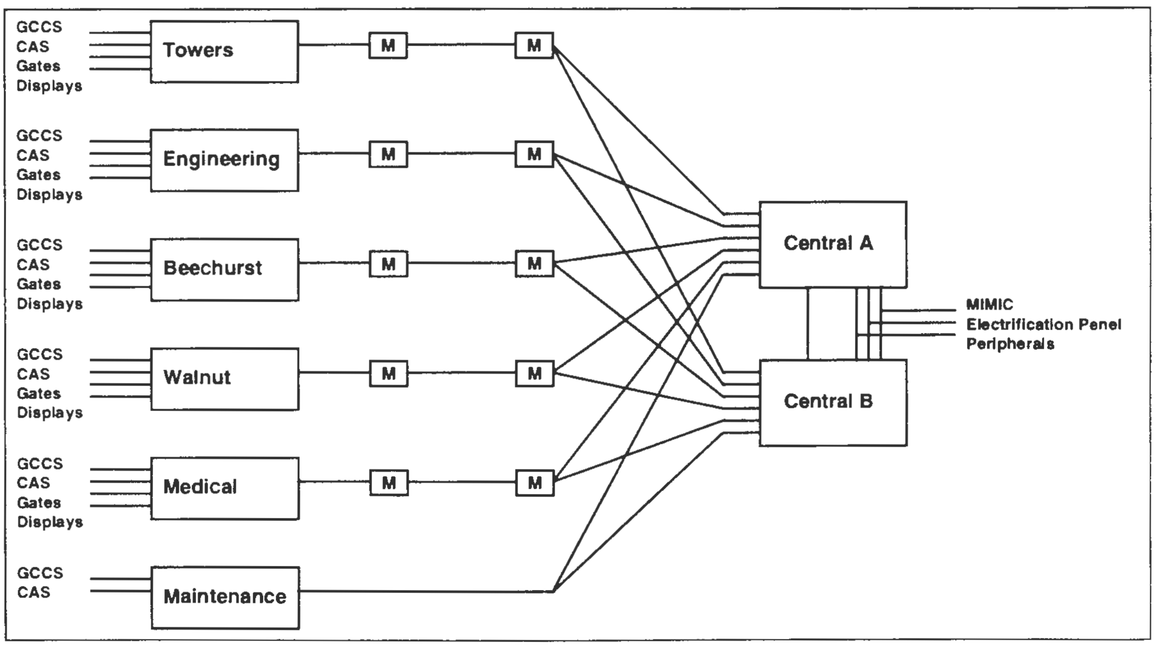


Figure 5. Interface Between Station Computers and Central Computers

4.1.4 Boarding Displays

While performing analysis on the computer platform alternatives, we also looked at programmable boarding displays. The proposed upgrade would include a serial port from the station computer to a chain of boarding displays. New displays that are available can be daisy-chained together, requiring only the one computer port mentioned (RS-232 or RS-422). One typical sign is 10.5" high, 6.3" wide, and 94" long, weighs 80lbs, and is capable of displaying 15 six-inch tall characters at a time. For this particular display, five different character scrolling speeds are available, with a memory capacity of 7200 characters (Alpha 790i, Adaptive Micro Systems[3], Inc.). These new signs would permit any message to be displayed at any time, using software control. Larger signs capable of displaying more characters at a time are also available. As of February, 1996, the price of the display mentioned (790i) was $4,000 each, with price breaks for a multiple quantity buy. Data Basics Corporation[4] is another supplier.

4.1.5 Central Computer Interfaces

Figure 6 shows the interfaces for the Central Computers. As described in Section 4.1.3, either RS-232 or RS-422 can be used to interface between the central computers and the modems (depending on the modems). RS-232 is shown on the figure since that is the electrical standard used on the existing system. The proposed upgraded computer system could use the existing 19.2K baud modems at the maximum data rate, given that modem-to-modem wiring can support those rates. If it is desired to replace the existing modems, that could be done as well (the computer hardware will support higher rates).

Using RS-422 electrical interfaces, lines connecting to the electrification panel, MIMIC, and peripherals have the capability of being shared by the dual central computers. Only the prime computer would be allowed to control the external devices. The backup computer would have its outputs disabled.

---

[3] Adaptive Micro Systems (800) 558-7022
7840 N. 86th Street
Milwaukee, WI 53224

[4] Data Basics Corporation (206) 431-1373
200 S.W. 176th
Seattle, WA 98166

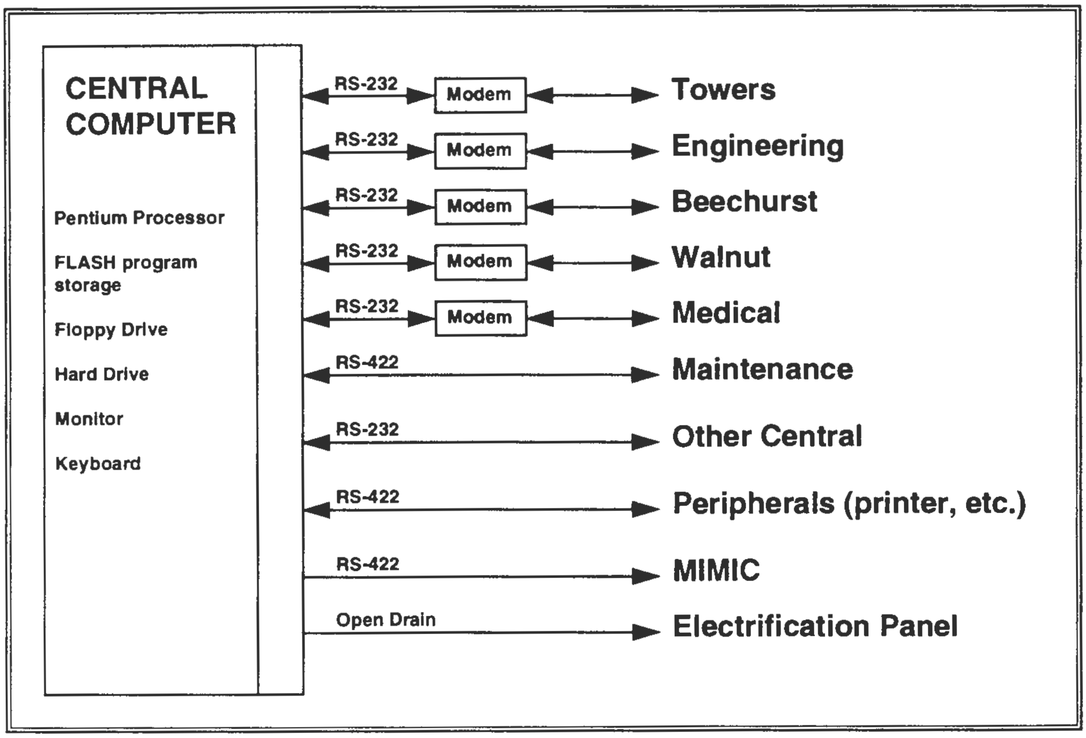


Figure 6. Central Computer Interfaces

4.2 Software Rehost

When the M-PRT software was designed and implemented in the mid-1970s, the limited throughput and storage capacities of the computing hardware heavily influenced the resulting product. To meet the timing requirements, most of the software was written in DEC PDP 11 assembly language and a specialized executive was required. With the phenomenal advances in computer hardware since that time, capacity constraints no longer apply. Therefore, as part of the computer upgrade, WVU has requested that a high order language and commercial operating system be recommended for use in the rehosted system.

In making selections for the language and operating system, we had the following goals:

- Minimize the technical, cost and schedule risks related to the software rehost
- Choose products that will be supported for the next 15 to 20 years
- Choose products with the lowest life cycle cost
- Choose development tools that are hosted on the target computer platform.

With these goals in mind, we considered the following:

- The existing software performs the functions needed to operate the PRT. Over the years, it has proven to be very reliable. To minimize the risk of introducing errors during the rehost, the rehosted software should conform to the original design and implementation as closely as possible.

- The appropriate choices of operating system and development tools can affect the reliability of the end item.
- The new software should be portable and readily understood to facilitate future maintenance and modification.

There is some conflict between the above considerations. For example, changes to the existing applications software can be minimized by literal translation of the assembly code and modifying the new operating system to exactly match the services provided by the M-PRT executive. However, this precludes gaining full advantage of the error detection capability of high order languages and will invalidate the vendor's support of the operating system. In addition, modifying the operating system may significantly increase costs since the source code will be needed. In addition, this use of a modified operating system may reduce portability and understandability.

4.2.1 High Order Language

Two languages, Ada and C, are more widely used for real time applications than any others. While some FORTRAN was used in the original code, not enough was used to compensate for the disadvantages of using a language that is no longer widely supported nor well suited for real time applications. Therefore we limited our evaluation to Ada and C/C++.

Although Ada was originally developed for the Department of Defense, over the years, Ada has become the "language of choice for safety-critical systems."[5] Although it had its shortcomings, it has been used in numerous non-military applications including aircraft avionics, air traffic control systems, train control systems, and biomedical systems. Based on articles that have appeared recently, the introduction of ISO 8652:1995 Ada standard has also increased the general level of enthusiasm for using Ada in non-military products.

C is widely used in embedded and non-embedded commercial applications. All of the real-time operating systems are bundled with a C compiler.

If we were starting from scratch to build a control system for the M-PRT system, Ada would be the most likely choice of high order language. However, given the considerations unique to the rehost effort that were mentioned above, C appears to be the most appropriate choice. Table 8 summarizes the language considerations related to the M-PRT software rehost effort.

Consideration	Ada	C
Code and Data Structure Compatibility	Moderate code and data structure redesign required	Minimal code and data structure redesign required
Automatic Code Translation	Not practical	Potential supplier found
Software Reliability Implications	Industry experience: Ada the best choice for new design or substantial redesign; compilers perform extensive error checking	Adequate for MPRT since minimal redesign is required and system is not large; use C++ compiler for error checking

[5] Richard Riehle, "An Ada for the Rest of Us," *Embedded Systems Programming*, November 1995.

Extent of use	Less than C but interest outside of DoD is growing	Very widespread - especially in PC and microprocessor applications
Integration with Real Time Operating Systems	3rd party; limits choices of operating systems	Tightly integrated with all operating systems; C++ also available for most
Compiler Availability	Moderate number of suppliers; few have X86 hosted development systems	Large number of suppliers; included with most operating systems

Table 8. Ada Vs C Comparison

Code and Data Structure Compatibility. The code and data structures used by C are very similar to those of the existing software, so literal translation from PDP 11 assembly language to C is straight forward. Literal translation to Ada is also feasible. However, it would require defining data structures that defeat the strong typing features that give Ada its exceptional error detection capability. In other words, it would nullify one of the primary advantages of Ada over C.

Automatic Code Translation. WVU has stated that their goal is to replace the existing computers without introducing a lot of new functionality. Since the changes are minimal, it is desirable to automate the code translation process.

Software Reliability Implications. Various sources have attributed the success of their projects to the use of Ada for reasons including: separation of the unit specification from the body; language-enforced checking that reduces the test effort; and higher level of abstraction for multi-tasking, bit manipulation, and data types. C has a reputation for allowing the programmer to develop code containing many errors. However, much of the error checking performed by Ada compilers is also performed by C++ compilers. Therefore, while the Ada programs are still generally the most reliable, reliable C programs can be developed by using good engineering practices and a C++ compiler.

4.2.2 Operating System

In analyzing each of the six qualifying operating systems, we wanted to answer the following questions:

- Will the OS be supported for the next 15-20 years?
- Does the OS contain the functions needed to support the M-PRT applications?
- Does an integrated, PC hosted, development tool set exist?
- What are the procurement and maintenance costs?

4.2.2.1 Product Life Cycle

While it is impossible to determine with certainty whether an operating system will still be supported 20 years from now, market share is an indication of the viability of the product. Additional factors that we considered include company age and whether or not it is publicly traded. Table 9 shows this information for each of the six operating systems under consideration and gives information for contacting the vendor.

4.2.2.2 OS Functionality

All of the operating systems (OSs) are essentially equivalent in terms of applicability to the existing M-PRT software design. Of the services each provides, the only ones that might be useful are similar for all of the OSs. They all provide UNIX style task control that is POSIX compliant. Of the remaining services required by the M-PRT software, timing and I/O are also uniformly provided since the recommended hardware configuration uses standard I/O interfaces. Unfortunately, none of the OSs provide task control equivalent to that provided by the M-PRT executive.

The task control concept incorporated in the M-PRT executive was specifically designed to support the operations concept for the M-PRT. Table 10 describes the executive service requests (ESRs) implemented in the executive and used by the applications programs.

Operating System	Vendor / Address	Internet Home Page	Telephone	Stock Symbol/ Date Founded	1994 Market Share[6]
Lynx	Lynx Real-Time Systems 2239 Samaritan Drive San Jose, CA 95124	http://www.lynx.com	800-255-LYNX 408-879-3900	privately held 1985	5%
OS-9	Microware Systems Corp. 1900 N.W. 114th Street Des Moines, IA 50325	http://www.microwar e.com	800-475-9000 515-224-1929	privately held 1977	9%
pSOS+	Integrated Systems, Inc. 3260 Jay Street Santa Clara, CA 95054	http://www.isi.com	408-980-1500	NASDAQ: INTS 1980	17%
Precise M/QX	Intermetrics Microsystems Software Inc. 733 Concord Avenue Cambridge, MA 02138	http://www.inmet.co m/MSD/imsi.htm	800-356-3594 617-661-0072	privately held 1970	?
VRTX32	Microtec Research, Inc. 2350 College Blvd. Santa Clara, CA 95054	http://www.mri.com	800-950-5554 408 980-1300	NASDAQ: MTEC* 1975	21%
VxWorks	WindRiver Systems 1010 Atlantic Avenue Alameda, CA 94501	http://www.wrs.com	510-748-4100	NASDAQ: WIND 1981	22%

* Acquisition by Mentor Graphics via stock swap announced October 10, 1995 - estimated value = $130 million.

Table 9. Real-Time Operating System Alternatives

[6] Source: Wessels, Arnold and Henderson Industry Report dated February 16, 1995

Name of ESR	ESR Function	OS Function*
Schedule Task	Schedule task to execute at a delta time(1/60 of a second to 36 hours.) One task may be scheduled multiple times.	none
Remove Scheduled Task	Delete the schedule for a specified application of a task	none
Schedule Periodic Task	Schedule a task to execute periodically beginning at a specified delta time	period, period run
Queue Task	Insert specified task into the FIFO dispatch queue for execution according to its priority	task_create, task_start
Exit Task	Return control to the Executive (issued at completion of every task)	exit
Suspend Task	Allows a main program to suspend itself while another tasks executes	pause
Transfer Data	Used to input (unrequested)data from the modem, CRT keyboard, teletype keyboard, destination select unit, downlink, and PD input.	aio_read
Input	Read data from a designated device (disk files, safetone I/O, station display, power output)	read
Output	Send data from designated memory locations to specified output device	write
Current Real Time	Get current time - 16 bit unsigned integer sixtieths of seconds	get_time
Get Current Date/Time	Get current data and time: day, hour, minute, second, and sixtieths of second	time, local_time
Set Current Date/Time	Initializes the date/time values	make_time set_time
Task Data Word	A word used to pass data from the requesting task to the task to be executed	task arguments
Arm Backup Computer	Enables the backup computer string to be available for switchover in the event of a prime string failure	none
System Status	Allows CAP to obtain the operational status of all M-PRT computers and the central SPE	none
Define Configuration	Identifies a station to be set inoperative	none
Switchover	Enables the prime computer string to direct the backup computer string assume the prime processing functions.	none
Reactivate Failed I/O Devices	Provides the capability to reactivate failed I/O devices in the central, station, or maintenance computers	none
Activate SPE	Directs the Executive to initialize the SPE	none
Report Error	Allows applications to report critical and non-critical errors to the operator	none

Table 10. M-PRT Software Executive Service Requests

*OS function names in Table 10 and in the following text are generic. Two functions are shown when both are needed to meet the ESR functional requirement.

MPRT Task Control Concept. The M-PRT executive was designed to meet requirements identified during detailed design of the applications software. The detailed design of the applications software was then built around the task control concept implemented in the executive. As implemented, the central concepts related to tasks in the M-PRT software are:

a. The applications software consists of small, single purpose modules referred to as "tasks." The term "task" applies to the module and the tasks it performs.

b. The executive maintains a queue of tasks waiting to be performed. A task is entered into the queue to process an external message or by request from another task.

c. Only one task is active at a time.

d. Once dispatched (put into execution by the executive) a task runs to completion, i.e., one application task cannot be preempted by another. Hardware interrupts are allowed, but most of the processing is performed later by a task.

e. Tasks can be scheduled to be performed after a specified delay. Thus the executive maintains two task queues: the priority ordered dispatch queue (b. above) and a time ordered (schedule) queue. When the specified time has elapsed the task request is moved to the dispatch queue.

f. Scheduled tasks can be marked for periodic execution.

g. Tasks can be removed from the time scheduled queue.

Item d imposes a requirement that a task must be completed in time to satisfy the latency constraints of all higher priority tasks. This is a significant feature of the M-PRT approach -- each task is performed in a quiet environment. Extensive use of global data is safe because no other task can change the data until the current task is complete. This avoids the need for many of the primitives specified by POSIX.

POSIX/UNIX Task Control Concept. The POSIX/UNIX task control concept is quite different from the M-PRT approach. UNIX was originally an operating system for time sharing using pseudo-parallel processing. It has been extended to real time applications and true parallel processing. Its approach to time sharing and parallel processing leads to significant differences from the M-PRT approach. In particular, to allow for parallel operation, tasks cannot assume that they will run serially. Most processing is performed in response to external messages. Most tasks are not closely coupled and do not directly share memory. Users must be protected from each other and time has to be allocated "fairly" so that processing is not limited to a single task. Thus, it is natural to use messages as a means for one task to initiate another. In a POSIX OS, a task is started by being "created". (The code is loaded unless it is already in memory. In any case a task control block is initiated.) Once a task starts it remains alive in one of three states: running, blocked, or ready. Table 11 describes the state transitions. Table 12 describes the commercial OS functions that can be used to approximate M-PRT task control.

POSIX State Transition	Description	M-PRT Application
· Running to blocked	· A task stops to wait for more work (a message) or other forms of blockage	· Can be used to approximate the time independent task control needed for M-PRT
· Running to ready	· A higher priority task is ready	· Not required
· Blocked to ready	· A block is removed (e.g., message arrives)	· Can be used to approximate the time independent task control needed for M-PRT
· Ready to running	· No other ready task has higher priority	· same

Table 11. Commercial Real-Time Operating System State Transitions

OS Function (generic name)	POSIX Function	Function
period	none	spawn a task to call a function periodically
task_create/ task_start	fork	create and activate a task, i.e., create a task control block and link it in the task queue by priority.
exit	exit	terminate task
pause	pause	suspend task
mq_open	mq_open	open a message queue
mq_close	mq_close	close a message queue
message_send	mq_send	add a message to a message queue by priority (with blocking optional)
message_receive	mq_receive	request a message from a message queue FIFO by priority (with blocking optional)
block	block	suspend task pending completion of a request, e.g., until a message is received
delay	sleep	suspend a task for a specified time period

Table 12. Commercial RTOS Functions Applicable to M-PRT Task Control

The following approaches can be used to approximate the time independent task control needed for M-PRT:

a. Task_Create/Start. Substitute *task_create/task_start* for the M-PRT QUEUE TASK ESR and *exit* for the EXIT TASK ESR. This change is minimal -- possibly an automatic translation.

b. Messages between tasks. Create and start one instance of each task at start up. Substitute a *message_send* for QUEUE. Add a *message_receive with blocking* request to the beginning of each task and loop back to the start at the end of each task, i.e., loop forever.

c. A combination of the above. Tasks that process events at a high rate should use the second option. The first option is simpler to implement and is fine for most tasks.

Missing Capability. POSIX operating systems do not include a straight forward approximation of the M-PRT SCHEDULE TASK ESR. This is a serious shortfall for the M-PRT application. Several forms of timing services are provided but all fall short of allowing one task to directly control the time at which a task is started or at which a message is sent to a task. Typically, the operating systems include various mechanisms (alarms, wakeups, timeouts) that can be set against various events (messages sent/received, semaphores, event flags, etc.) Each is designed to time out an event and notify the requesting task when the time-out occurs. For example, when one task sends a message to another, the sending task can set a time-out to verify that the message was received and/or receiving task can time out on a *message_receive*.

Three work-arounds are feasible:

a. A utility can be written to replace the M-PRT SCHEDULE ESR. The utility would enter each request in a time ordered queue. A periodic task (operating six times per second to match the M-PRT design) would issue a *send_message* request when the next task is due. (Alternatively, the task could be created if the Create/Start approach is used.)

b. The requesting task can *create/start* the task to be scheduled, passing the delay time to the scheduled task. The scheduled task would then *delay* for the specified time, then proceed until processing is complete and *exit*.

c. The requesting task can *delay* before issuing its request. This requires the task to defer its request until the rest of its processing is complete. This also does not allow the scheduling to be done by a shared subroutine (e.g., the stop tone release subroutine which is used extensively by tasks performing in-channel processing.) Also the requesting task must be single purpose, i.e., it cannot process additional messages while waiting to schedule a follow-on task. Thus the requesting task must be controlled using the *task_create/destroy* approach rather than the *message_receive with blocking* approach.

The first approach is recommended because it requires the least code modification and involves the least risk since it centralizes the change in a moderate amount of new code.

Periodic task control under POSIX is straight forward. The SCHEDULE PERIODIC TASK ESR can be replaced by a *task_create/start*. When it starts, the periodic task can *delay* for the specified period, then proceed until processing is complete and loop back to *delay* again. An alternative is to use *period* functions to activate periodic tasks. The period functions could use either the *task_create/start* or *the send_message* approach.

4.2.2.3 Development Tools. In the analysis, we looked at the tools available with each real-time operating system. The existence of a fully integrated development tool set can significantly influence the procurement cost since most of the costs are in software development labor.

We gathered data from the Internet World Wide Web, from vendor literature, and by talking directly to vendors. We first talked to Lynx Real-Time Systems and Wind River Systems who visited the Boeing facility. We then talked to Microware, Integrated Systems, Microtec Research, and Green Hills at an Embedded Computing Show that was held at a nearby hotel. Intermetrics was contacted by telephone. We also conducted follow up telephone conversations with the technical support people at several of the vendors.

We found that each of the vendors delivers its operating system with a C compiler, and most include a C++ compiler. Integrated tool sets are available for all of the systems, however Intermetrics does not have a tool set that runs on the X86 platform. There is some variation in the capabilities provided by the tool sets but all are vastly superior to the tools that were commercially available during the original M-PRT software development. Table 13 summarizes the information that we collected about the various tool sets. We were most impressed by the capabilities of the Green Hills development tools. These have been integrated with pSOS and VxWorks.

We found out that our initial information about the Precise Solution tool set was incorrect. It turns out that they only have 68000 based development systems. As a result, we eliminated it from further consideration.

4.2.2.4 Procurement and Maintenance Costs.

Table 14 summarizes the pricing information on the five operating systems that remained under consideration. We assumed that we would need four development seats for rehosting the operational and real-time simulation software. For OS-9, pSOS+, and VXWorks it turned out that it was less expensive to buy the team development environment (five or ten users) than it was to buy four seats. Under our baseline configuration of a dual Central and six single processor stations, eight target systems would be needed. Since the Lynx development system and target system both use Lynx OS, only seven target systems are needed if Lynx is selected. Some of the vendors offer a university discount; the rules vary on whether or not the discount can be applied for the M-PRT upgrade.

Table 13 also shows the prices for yearly maintenance fees are also shown. Payment of the maintenance fee procures version updates as they are released. While there is a significant variation in these prices, they are all small compared to other M-PRT system maintenance costs.

Operating System	Compiler	Development System	Comments
Lynx	GNU C, C++ (Free Software Foundation)	PosixWorks Self-hosted	· True operating system, largest with most overhead · POSIX compliant (real-time UNIX) · Good tool set but limited to those that run under LynxOS · TotalView allows real-time debugging of distributed systems · Supports memory management H/W
OS-9	Commercial	FasTrak Windows or self-hosted	· Second most comprehensive dev system · Supports memory management H/W ? · OS kernel + TCP/IP more than adequate
pSOS	Commercial (MetaWare or Green Hills C, or C++)	ISI or pRISM (Green Hills Multi) Windows host	· Green Hills Multi looks like the best development system. Has powerful debug tools and version control · POSIX compliant for services provided (adequate) · Loads applications into protected mode memory
VRTX32	Commercial C and C++	XRAY MasterWorks Windows host	· Adequate dev system · Supports X86 protected mode - provides memory segmentation
VxWorks	Enhanced GNU; also integrated with Green Hills C, C++ and Ada	Tornado Windows host	· Good OS, adequate dev system. · Can augment with Green Hills Multi. · WindView and Stethoscope are good tools for runtime debugging but are not included in price · Helpful reps - help work design problems
Precise M/QX	Commercial; C++ still in development	Precise Solution Windows host	· Executive kernel with minimal functions wrapped around it - may be too small · Development tools have not been hosted on X86 platform · Royalty-free source code

Table 13. Development Tools Available with Operating Systems

4.2.2.5 Summary

Based on our evaluation, there is no operating system that clearly stands out over the others as the best choice for the M-PRT upgrade. The technical capabilities are approximately equivalent for most of the systems and they all have integrated development tool suites. To maximize the likelihood that the OS will be supported for the next 15 to 20 years, we recommend choosing one of the systems with the largest market share. An industry source believes that the big players for the future will be VXWorks from Wind River Systems and pSOS from Integrated Systems, Inc. While there is some variation in price, the operating system's procurement cost is insignificant in relation to the cost of rehosting the software and its maintenance cost is small relative to other M-PRT operations and maintenance costs. Therefore, price will only be a significant factor if everything else is equal. This brings us to an important consideration that may end up driving the decision -- contractor experience with one of the candidate operating systems. We recommend that the selected upgrade contractor make the final operating system selection based on the experience of its personnel and the OS capabilities and tool sets available at that time.

Operating System	Development System 4 seats (C++)	8 Target Systems	Yearly Maintenance 1 Development System	Yearly Maintenance 8 Target Systems	University Discount	Comment
Lynx	$12,338	$10,160	$2,468	$560	No	only 7 target seats required since self-hosted
OS-9	$9,950	$7,200	$750	$1,600	10%	5 user license; will donate to universities if incorporated in curriculum
pSOS+	$14,300	$3,200	$2,860	$0	25%	10 user license; includes $3900 for 1 pRISM seat
VRTX32	$12,600	$1,600	$630	$0	15%	Includes 15% discount for > 3 dev units; no maint fee for target; discounts for multi-year maint avail
VxWorks	$24,750	$7,420	$2,800	$0	?	5 user license; no maint fee for target; does not include Windview or Stethoscope
Column Comments			1 unit	8 units		

Table 14. Operating System Cost Data

4.2.3 Conversion Approaches

We have developed an approach to rehosting the software that gives high priority to retaining the existing design. This approach is summarized in Figure 7.

The first activity is to review and update the design documentation. The contractor and M-PRT should work together during this review, to ensure that any changes made after deployment, such as implementation of circulation mode, are included in the upgrade. Any additional changes needed to improve operations can also be made at this time.

If automatic code translation has been selected, it can be done while the update is in progress. As shown in the figure, the existing code is automatically translated to C. The resulting code is then modified to handle special situations (awkward and/or inoperable translations) and improve readability. Modifications are also made to compensate for differences between the M-PRT executive and the selected real-time operating system. To the extent practical, the operating system is used in a way that does not change the M-PRT applications software design, i.e., retain the existing task flow even though current operating systems are not designed to support it. The resulting modules are reviewed against the updated design. This peer review is a very critical step in the process. As shown, the changes resulting from the review are then implemented and reviewed.

The upper right-hand corner shows the existing test descriptions and procedures being updated. Most of the updates are required to conform to the new computer hardware architecture. The rehosted software is integrated incrementally and tested against the updated test procedures. On completion, the software will be ready for subsystem testing.

4.2.3.1 Documentation Conversion Approaches

In conjunction with the computer platform and software upgrade, existing documentation will require updates. Key reasons for the updates include:

- New computer hardware configuration

- Replacement of Executive functions and Executive Service Requests (ESRs) with commercial operating system.
- New capability to allow operator to enter ASCII characters for display on the station boarding displays
- Change from system string reconfiguration to station by station reconfiguration.
- Incorporation of existing Advance Document Revision Notices (ADRNs) and Specification Change Notices (SCNs).

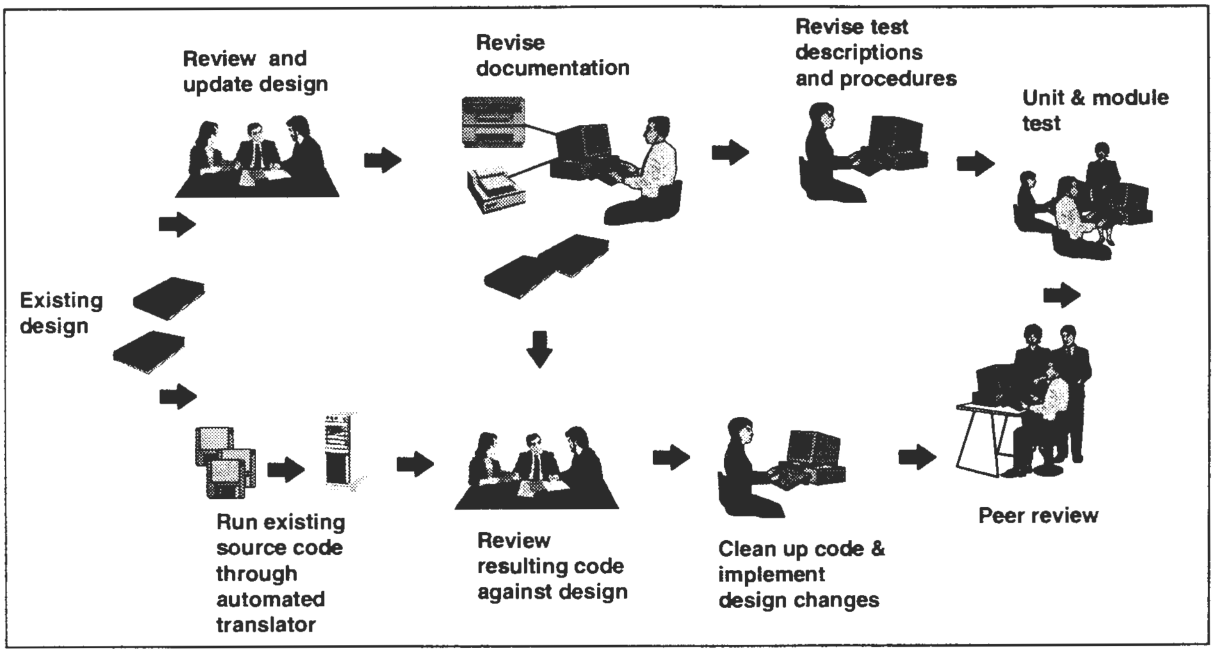


Figure 7. Software Rehost Approach Uses Existing Design and Code

Although the existing documentation is not available on magnetic media, we recommend that the computer upgrade include development of electronic versions of the documentation. The resulting files could be written onto CD-ROM for easy reference. We performed a brief investigation to determine a method for accomplishing this conversion.

Text Paragraphs. The text pages can be easily scanned, run through an optical character reader, and entered into a word processing file. This process was successfully tested by using a standard fax machine to transmit a typewritten document text page to a Dell Optiplex 466/Le computer running Delrina WinFax Pro version 4.0. The optical character reader feature in WinFax Pro was used to create a text file. The AutoFormat and Grammar checking capabilities in Microsoft Word for Windows 6.0 were applied to the text file, resulting in a clean document page.

Tables. The procedure used to convert paragraphs was applied to a page containing a table but with unsatisfactory results. Further investigation is required.

Graphics. Many of the original graphics are contained in Boeing's files. If no changes are required, an original graphic can be scanned and inserted into rebuilt documents. Graphics that require changes should be rebuilt. We tested this concept using Visio 3.0 for the figure 3.2.1.2.2-1 from the CAP Part 2, CISF General Flow. The result is shown in figure 8. We estimate that a trained user of Visio could build a flow chart of this complexity in 20 to 30 minutes.

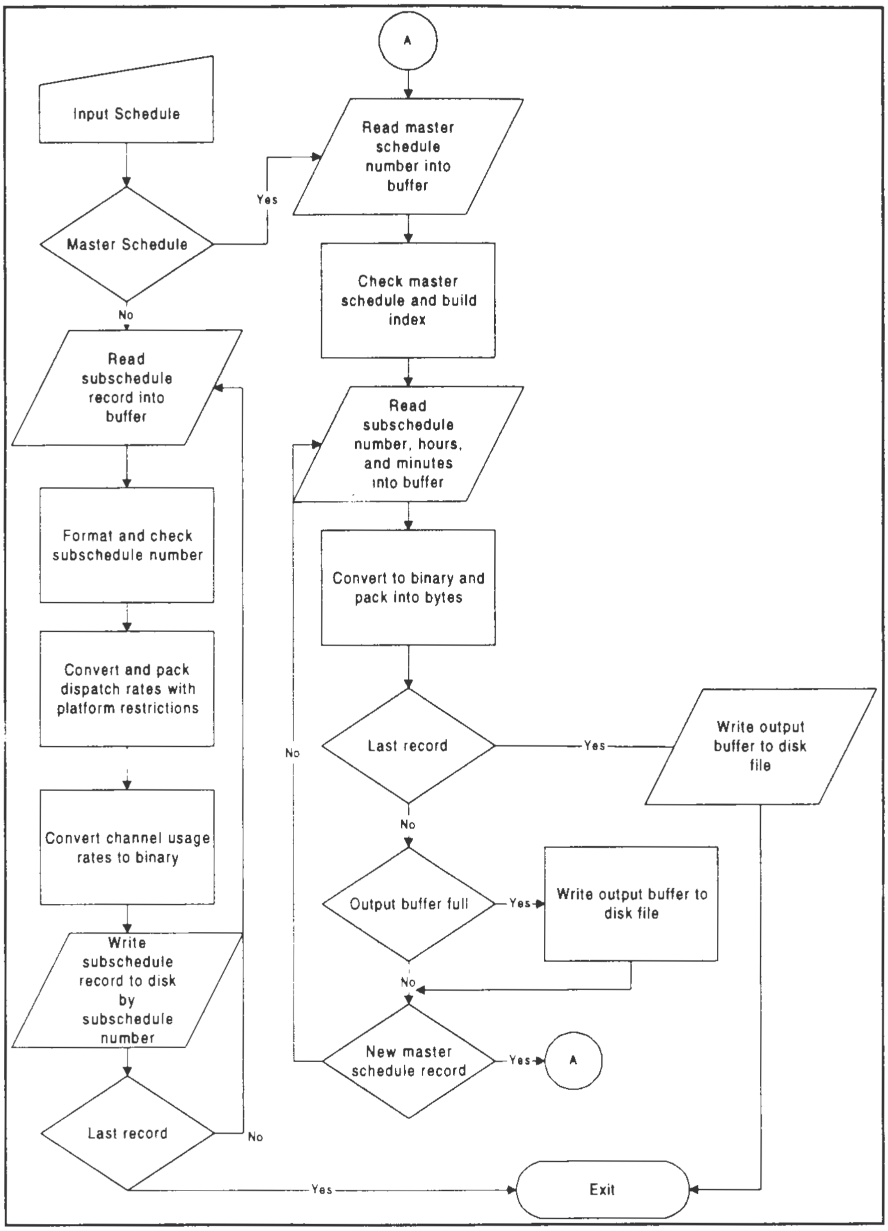


Figure 8. Example Flow Chart Rebuilt Using Visio 3.0

4.2.3.2 Program Code Conversion Approaches

Two approaches can be taken to replace the application software with portable high order language (HOL) software.

1. Translate the assembly code to HOL, automatically or manually. Translated assembly code shows its origin, but reads as well as the original code. The original is well commented, reading like the detailed design document, hence inclusion of the comments results in well-commented code. The translation can be done literally or with restructuring. Literal translation is easier to verify against the original code and is more readily obtained from an automatic translator. However, it requires extensive use of GO TOs. Eliminating GO TOs

requires extensive restructuring. While restructuring provides cleaner code, it also increases the risk of translation error. An automatic translator may be programmed to restructure simple cases and would be less likely to introduce errors.

2. Recode directly from the detailed design (Part 2 Specifications flow charts).

Automatic Translation. Automatic translation has the potential for inexpensive generation of the majority of the software modules. We recommend this approach since there are few changes required to the M-PRT software functionality. (Unfortunately, the original source code is not available in machine readable form and attempts to scan the listings have been successful to date. A version of the source code that was retyped by the WVU software maintenance engineer, but not proofed, is available.) The modules generated by the automatic translator will need a general clean up, rigorous peer review against the updated design, and thorough testing. The clean up will go better if the original code is initially included as comments. A follow up pass can eliminate the original code and leave the original comments.

We have located a company, Micro-Processor Services, Inc., that specializes in the design, development, and custom configuration of language translation tools to convert existing software applications from one language to another. They have stated that they could translate PDP11 assembly language to C for between $5,000 and $10,000. While they have not previously performed a PDP-11 translation, they believe it would not be difficult to modify their 68000 to C translator to accept PDP-11 assembly language as input. This would involve writing a new front-end syntax analyzer.

Micro-Processor Services, Inc. is located at 92 Stone Hurst Lane,
Dix Mills, NY, 11746.
Telephone: (516) 499-4461
E-mail: mpsinc@netusa.net
Internet: http://www.mpsinc.com

Manual Translation

If it turns out that automatic translation is not practical, recoding should be performed based on the updated design and the existing code. As in the automatic translation process, peer reviews of the recoded modules and thorough testing would be performed.

Manual translation offers the advantage of some restructuring. For example

```
              CMP     R0,R1
              BGT     LABLE1
              BLT     LABLE2
               (code section 1)
              BR      LABLE3
LABLE1:       (code section 2)
              BR      LABLE3
LABLE2:       (code section 3)
LABLE3:       (code section 4)
```

can be recoded in C as

```
If (R0==R1)       {statement[s] 1;}
      Else If (R0>R1)   {statement[s] 2;}
      Else                          {statement[s] 3;}
{statement[s] 4;}
```

A literal translation would be

```
              If (R0>R1)  Go To LABLE1
              If (R0<R1)  Go To LABLE2
              {statement[s] 1;}
               Go To LABLE3
LABLE1:       {statement[s] 2;}
               Go To LABLE3
LABLE2:       {statement[s] 3;}
LABLE3:       {statement[s] 4;}
```

Recode from the Detailed Design. The second option allows the software to use the structuring standards supported by the HOL. If this method is used the data should also be restructured to make maximum use of the HOL error detection capability. This would be the best option if the HOL choice is Ada.

Potential Problems. Regardless of the method used care must be taken to avoid translation errors. Two potential problems are:

- The current code packs and unpacks bytes. Signed bytes need special consideration . On the PDP11 bytes are moved to registers with sign extension (all 1's in the upper byte). Moving a byte to a memory word does not sign extend. (The upper byte is unchanged.) An HOL will not make that distinction. The compiler should flag incompatible assignments (e.g., moving a character to an integer). That will flag potential problems which need to be considered on a case by case basis.

- The translations of an unsigned-compare and a logical-shift need to verified.

4.2.3.3 Data Base

The options for recoding the data base are similar to those for the code: directly translate the source either automatically or manually, or restructure and recreate the data. Automatic translation is recommended because it is least likely to introduce errors.

In principle, the best way to recreate the data is to read it from the load modules. It may be possible to link the data load modules with a program designed to access the global data and output appropriately formatted files.

An alternative method is to use the data base source code generated at WVU. Since that code was manually entered , it should be assembled and linked against the load map then compared to the corresponding load modules at WVU. By using automatic translation the original comments can easily be included. The translated data definition can track the original code line for line, hence manual verification against the original printed source code documents would be feasible if automatic verification is not. Once verified, the data source code can be translated to HOL data statements. For either automatic or manual translation of the source code, it is important to properly track the use of RADIX10 (base 10) vs. RADIX8 (octal) numeric data. These are explicitly called out in the source. However, RADIX10 is occasionally over ridden by a leading "0" to switch to an octal number . RADIX8 is overridden using a trailing "." to switch to base 10.

4.2.4. Changes to Phase II Design

Although most of the software rehost is a direct conversion from the existing design, some changes are required. In addition, there are other changes that, if made, would improve the operator interface or make the system more appealing to the passengers.

4.2.4.1 Required Changes

Executive. The rehosted Executive Program will be much smaller than the existing version due to the use of a real-time operating system and the elimination of the backup computer at the stations. In the rehosted software, the Executive Program will include the following functions:

- Initialization --establish which computer is prime, load safe data, transfer safe data to the backup computer, download stations, start applications tasks.
- System Status Monitoring -- the prime central verifies that the station computers and the backup central are operating; the backup central verifies that the prime central is running
- Reconfiguration--enables the backup central to seize control if the prime central is not operating properly and allows the prime central to transfer control to the backup central on operator command.
- Data Synchronization--transfers variable data from the prime to the backup computer to synchronize processing.
- Central/Station Clock Synchronization--synchronizes the station clocks to the prime central clock. The current system does not resynchronize because all clocks are synchronized to the 60 hertz power supply. Resynchronization capability will not need to be added unless relative clock drift exceeds 100 ms per day.
- Task Scheduling--retains the M-PRT executive task time scheduling capability.

Circulation Mode. Circulation Mode was established by M-PRT operations personnel who determined that it was most efficient to have vehicles stop at every station during low demand periods. They implemented it into the existing system using a special schedule and a patch to the software.

In the rehosted software, we recommend that the following operator command be added to the CAP design:

Command	Parameters	Action
Circulation Mode	• Dispatch Rate	Set mode to circulation and notify all stations

To implement this command, two types of changes are required to PSAP. First, the vehicle management module (mode change or schedule control task) needs to be modified to schedule the

Destination Request Processing task to execute at the specified dispatch rate with "all-stations" as the destination. Second, the Guideway Switch Control, Guideway Switch Verification , Channel Switch Control, and Channel Switch Verification tasks need to be modified to recognize that a vehicle with an "all-stations" destination is to be switched into the station and into a through channel for off-line stations. The simplest implementation is to define a unique station ID (such as 99) to mean "all stations." A more flexible implementation is to use bit mapped destinations and change the current destination check against station ID to a bit test against a station mask. This would allow extension of the all-station concept to a multiple station concept in which a vehicle could be assigned to two or more destinations. This would work well in demand mode with multiple destinations being assigned according to passenger requests. The vehicle would only being switched into a station that (1) that is the destination of a passenger on the vehicle or (2) has a passenger request for a downstream station.

4.2.4.2 Other Potential Changes

Programmable Passenger Boarding Displays (PBDs). Replacement of the existing boarding displays with programmable passenger boarding displays would make the system more friendly to the passengers. M-PRT operations personnel have expressed a desire to be able to allow the central operator to enter text messages for display to the passengers. For example, if the guideway power was down between Beechurst and Engineering, the operator would be able to display a message to northbound passengers at Beechurst and Walnut to explain the situation and let them know when service is expected to resume. This message could be continuously scrolled on the PBD.

Typically, a programmable PBD can store up to 24 pre-canned messages. Destinations and frequently used messages are pre-loaded and initiated by identifier. It is possible to implement the programmable PBDs as a stand-alone system with a simple serial interface to the central computer, however, we recommend that control of the PBDs be integrated with the rest of the operational software. To accomplish this, the CAP Operator Commands module needs to be modified to provide the following new commands:

Command	Parameters	Action
Set PBD Message	• Station, Channel • Message ID • Message Text	Display stored text message for the specified message number in the specified PBD; accept new text; store in central data base; send to station for storage in the PBD at the specified channel.
Display PBD Message	• Station, Channel • Message ID List	Notify station to display the specified string of messages on the PBD at the specified channel.

To support this function, a copy and paste capability should be added to the operator interface to make it easy for the operator to send the same message text to multiple PBDs.

In PSAP, new tasks need to be added to send the new messages to the PBDs. The current boarding display task may need to be modified to conform to the new PBD interface.

Improved Operator Controls & Displays

Currently all operator displays use text only. There can be only one display at a time. All operator commands are made by typing characters and pressing function keys. With modern computing hardware and software, significant improvements could be made to the operator interface. For example, a graphical vehicle location, similar in appearance to the mimic board, that shows each vehicle ID at its current location could be added. The operator could click the mouse on a vehicle ID to display that vehicle's status.

If these types of improvements are desired, a human engineering task should be included in the computer upgrade program to determine what changes would be beneficial to system operations.

Event Logging

Currently the event logging outputs operator actions, forced displays and vehicle locations to the Decwriter. This process generates a large amount of paper that may or not be looked at by the operations personnel. As part of the upgrade, events could be logged to disk rather than paper. If the operator needed to review something, a command could be added to let them look at the event log for a specified date and time. Software would be added to Central that would make a copy of the event log, then search for the specified time period and display it to the operator.

4.3 Existing and New Technology

We conducted a detailed investigation of the existing and new transit control system technologies identified in section 3.3. We found that at this time there is no proven technology available for near-term implementation that would improve M-PRT operations and maintenance.

4.3.1 Existing Technology

As is noted in 3.3.1 we contacted existing transit properties to determine if there are any currently available technologies that could be used by M-PRT to enhance operations or maintenance. The discussions with representative operating properties centered around their experience with computers, software and train (vehicle) control systems. A summary of this information is shown in table 14. Information about their computer upgrading and software rehosting activities was included in section 3.3.1. As a result of our discussions, we concluded that:

- There are no operations and maintenance advantages to be gained from the technology used on existing transit systems. However, there are benefits to be gained from their operational "lessons learned."
- A number of transit systems have upgraded their computer systems and rehosted their software. There is no definite trend toward any one computer system or operating system.
- No system has implemented a change in their control system strategy.

Analysis of information received from existing systems.

a. Most properties segregate the computer system to two levels - the central supervisory system, and the train (vehicle) control computer. This is due to a segregation in computer functions. The train control computer is usually supplied with the control system. The central computer, which is usually used for system supervisory functions, is at the discretion of the property. Most of the central computers are redundant in design and some are triplex. The supplier of the computer varies and there is not a preference to any one particular vendor.

b. The control system suppliers vary but there is a large group of AEG/WECO users. This is because of the number of systems that this group has deployed for airport service. Most of the properties that are not train systems are shuttle type systems where the control technology used is not as complex as M-PRT. The closest system to M-PRT operations is AirTrans and they use General Railway Signal (GRS) fixed block control.

c. Most of the computer maintenance is either done by service contract or done by the control system supplier. None of the properties does their own computer maintenance.

d. The software used in the system is usually the proprietary design of the control system supplier.

e. A number of systems have upgraded their computer systems and rehosted the software. There is no trend toward using any particular computer system or software language. There appears to be "leaning" toward the 486 architecture.

f. No system has made any changes in their basic control system strategy; i.e., a change from fixed block to moving block.

System	Computer System	Train Control System	Computer Maintenance	Software
O'Hare Airport Transit System	Central - redundant DEC MicroVAX	MATRA	MATRA	MATRA Design
SeaTac Airport Transit System	Central - single HP1000	WECO	Service contract	WECO design in FORTRAN
New Denver Airport	AEG/WECO	AEG/WECO	Done By AEG/WECO	AEG/WECO
DFW AirTrans System	Modular Computer Systems	GRS	Service Contract	Assembly Language
Miami Metromover	Central - Intel 486 based	AEG/WECO	AEG/WECO	N/A
Bay Area Rapid Transit (BART)	Central - Tandem Triplex	Number of Suppliers	N/A	N/A
San Francisco MUNI	Central - Triplex IBM PS-2 base	Alcatel	Alcatel	Alcatel
Vancouver Sky Train	Central/Wayside IBM/486 PC's	Alcatel	Alcatel	Alcatel
Washington, DC Metro	DEC VMS oriented	Number of Suppliers	Service Contract	N/A

Table 15. Existing Systems Technology

Conclusions

The technology used by existing systems does not appear to offer any large advantages for M-PRT, other than to be aware of lessons learned. The AirTrans system is the closest to M-PRT in operational similarity. This system has upgraded its computers, but always stayed with the same vendor. They have also looked at rehosting the software and going to a higher order language, but have not incorporated this change. This is not to say that they consider going to a higher order language risky, they have not yet seen the necessity to do so.

To date, none of the properties have incorporated fundamental changes to their control systems. However, there is a trend to take advantage of the latest available computer technology when upgrading. This is apparent in the Vancouver SkyTrain and Washington DC Metro upgrades to the latest IBM and DEC systems.

4.3.2 New Control System Technology

We conducted a detailed examination of the new communication-based control technology alternatives that are potentially available to M-PRT either now or in the near future. These alternatives, identified in section 3.3.3, include nine technologies. Each of these technologies offers the following operations and maintenance advantages to the present system:

- The capability for moving block control which would allow shorter headway operations.
- The elimination of some, or most, of the station electronics and guideway equipment, including equipment racks and electronics, guideway antenna loops, and presence detectors. This provides a significant reduction in maintenance requirements

When considering communication-based technology for application to M-PRT, there are two unique aspects that must be recognized: (1) the majority of the new system technology is in the process of being developed, tested or demonstrated and has never been deployed; and (2) the primary application of the control technology is for railroad industry operations. While this does not necessarily mean that there is a high degree of risk in application of the technology to M-PRT, some degree of caution is required when assessing how, if, or when, these control systems may be implemented.

Taking both the advantages and the limitations into consideration, we concluded that even though there are potential O&M advantages to be gained by applying communication-based control technologies to M-PRT, the developmental nature of the majority of these technologies make it too early to recommend a specific system. It is possible, however, to use part of the M-PRT system during off-hours to test or demonstrate a new control system technology.

4.3.2.1 Status of Communication-Based Control Technology

For this study, we contacted the vendors shown in Table 6. In most cases the vendor provided technical information on their particular system and responded to technical questions. The major area of technology development is determining the method by which communications are made between the wayside and the vehicle.

There are three types of wayside-to-vehicle communication methods being investigated or used by communication-based control suppliers.

Inductive communications: Similar to M-PRT, allows high capacity, bi-directional communications. Requires guideway, or track mounted continuous antenna loops and vehicle mounted antenna. Inductive communications have been used in the transit industry on a number of applications and, thus, have the advantage of operational experience.

Radio Based communications:

Leaky Coax - An RF (Radio Frequency) based distributed antenna, bi-directional system. Requires a continuous guideway, or track mounted coaxial cable and vehicle mounted antenna. Most of the advantages of leaky coax have been superseded by the RF technology noted below.

RF - Radio Frequency (RF) Communications, free-space or point source bi-directional communications. Requires a wayside base station and antenna which transmits to a vehicle mounted antenna and receiving unit. Systems use VHF, UHF, or spread spectrum technology. The direction of the industry is toward spread-spectrum radio which is a modulation method that spreads digital information over a wide bandwidth to negate the effects of signal interference. Spread Spectrum radio is line-of-sight and presently uses the 900 MHz band or the 2.4 GHz Industrial, Scientific, and Medical (ISM) band. The advantages of spread spectrum technology are: resistance to jamming and interference, and use of frequency bands that do not require FCC licensing.

Table 16 provides an overall comparison of the present M-PRT system with the communication -based control systems. It compares the functionality of the vehicle, wayside, and central subsystems. The communications method between wayside/vehicle and wayside/central is noted. It points out the system architecture and a brief description of the control strategy being used. The table addresses where safety critical processing occurs-- smart vehicle, smart wayside, or some combination of the two. We have also noted whether or not the new communication-based control technology can be overlaid onto the old system for demonstration and testing (this will be discussed further below). Headway design capabilities are shown. Finally, we have indicated whether the system design uses open or proprietary architecture. The tendency of the suppliers is to provide a proprietary design which allows open protocols at the communications interface.

Other Technology

The emphasis has been on communication-based technology which is applicable to the transit, or rail, industry. This does not imply that there are not other technologies in use, or in development, that may have potential application to M-PRT. The biggest impediment to use of other technology is the proof of safety when applied to a people-moving system. Some technologies that may have potential: cellular telephone technology used in determining police car locations; and Global Positioning System (GPS) location technology used for Federal Aviation Administration (FAA) upgrades to aircraft landing approach. The tailoring of these technologies for use at M-PRT would require some unique solutions, particularly in the station areas.

System/ Element	Present M-PRT System	AEG FLEXIBLOKã	GRS ATLASã	SELTRAC ALCATEL	BOEING (AGRT) ODDCAS	AATC (BART) HMK
Architecture Description	• Central Supervisory-overall system monitoring & fleet management • Wayside decentralized control of vehicles using point follower strategy • Independent collision avoidance • Vehicle responds to station commands & monitors speed, brakes, on-board status • Open architecture	• Central supervisory control • Regional wayside automatic train control for interlocking, vital/non-vital equipment control • Vehicle vital computer calculates safe separation • Design to incorporate open interface protocols	• Central supervisory control • Wayside communication sector control calculates & communicates closest obstacle to vehicle • Vehicle determines absolute position, reports to wayside, obtains obstacle information & generates speed limit profile • Design to incorporate open interface protocols	• Central system management control center • Wayside vehicle control zones primarily responsible for safe train separation • Vehicle control interprets commands from the wayside & controls the vehicle within velocity & distance limits • Presently proprietary architecture	• Baseline design uses M-PRT architecture - Central supervisory functions - Decentralizes control to local level which assures safe separation for headways down to 3 sec - On-board processor shares portion of safe separation assurance function • Open architecture	• Central supervisory control • Wayside control zones calculates & enforces safe separation & vehicle position • Vehicle on-board control limited to speed, brake & vehicle status functions • Application of open/proprietary architecture to be determined
Vehicle Functions	• Vehicle Control & Communications System (VCCS), in response to wayside command VCCS generates - Speed, brake, door & switch commands - Responds to wayside FSK messages - Calculates & responds to overspeed condition	• Vehicle vital computer calculates - location, safe separation, overspeed, switch control & interlocks, speed & braking commands, station stop & door commands - "Virtual occupancy" & "conflict point" data calculation • Position updates from wayside "norming" points monitors vehicle/station alarms	• On-board processor has infrastructure & vehicle parameter data base - Continuously calculates absolute position from wayside beacon, updates & distance traveled calculation - Reports position to wayside - Determines distance to obstacle each comm cycle - Generates speed limit profile & safe separation to obstacle - Monitors overspeed	• Vehicle on-board control (redundant microprocessors) - Interprets commands from wayside - Controls vehicle within velocity & distance limits command by wayside - Transmits vehicle position, velocity & status to wayside - Provides overspeed protection	• Vehicle command & control - Control & safety of vehicle - Uses on-board odometer data & communicates to wayside speed & position reports - Controls vehicle speed & braking - Provides overspeed protection - Monitors doors & interlocks	• On-board train unit - Accepts commands from wayside & enforces movement as commanded - Provides speed & acceleration control
Vehicle/Wayside Communications	• Bidirectional inductive coupling through embedded antenna loops • Presence detectors monitor vehicle position	• Continuous full duplex data communications - Can use RF techniques or inductive techniques	• Bidirectional RF link for data communications - Presently evaluating spread spectrum radio link	• Bidirectional inductive data transmission system - Inductive loop length up to 3.2 KM • Vehicle position detection through inductive loop	• Bidirectional communications through inductive communication antenna loops - Wayside communications & collision avoidance communications • Uses presence detectors	• Spread spectrum radio - Time multiplexed communications
Wayside Functions	• Station Computer & Station Electronics (SCCS) - Generates vehicle synchronous point follower - Dispatches vehicle to point - Control destination selection faregates boarding displays, concourse display • Guideway Command & Control System (GCCS) - Speed tones, switch tones, FSK messages, stop tones, calibration, presence detection • Collision Avoidance System (CAS) - Safe tone - Switch latch - Disparity detection	• Regional control computers - Controls interlocking - Communicates with wayside on each side of hand-over - Tracks vehicles in region - Forwards information to train for safe separation calculation - Communicates routing information to train • Passive wayside devices allow vehicle position update (norming points)	• Wayside sector controller - Reports location of closest obstacle to vehicle - Tracks location of all vehicles in sector - Monitors switches & route alignments - Updates sector speed restrictions • Location beacons provide data to vehicle in order to zero position errors • Communicates with other wayside sectors	• Vehicle control center - Primarily responsible for assuring safe separation - Monitors train position & velocity - Issues commands to vehicle for updated safe stopping point & maximum allowable velocity - Controls switches, trip stops & signals - Communicates to adjacent control centers & system management center	• Guideway command & control - Monitors vehicle-to-vehicle headway & commands position corrections - Controls dispatches, merge/diverge, stops, door operations - Includes wayside collision avoidance safe-to-proceed signaling through inductive communication loops	• Wayside control zone - Station computer determines train position based on RF propagation of time between train & wayside comm - Determines stopping distance, safe speed acceleration commands - Calculates position of all trains in system - Has track infrastructure data base - Communicates to other wayside control zones by RF link
Wayside/Central Communications	• Dedicated land lines	• Dedicated land links - Prefer fiber optics for vital communications	• Dedicated land lines	• Dedicated land lines	• Dedicated land lines	• Dedicated land lines
Central Functions	• MIMIC display • Electrification control • I/O Supervisory control • System status	• Supervisory control • Electrification control • Monitors regions	• Supervisory functions - Operations, schedules - Electrification control	• System management center - Supervisory functions - Displays, electrical power interface - Fleet management	• Supervisory functions - Displays - Electrification control - Fleet management	• Supervisory functions - Displays - Electrification control - Train management
Headway Design	15 sec	• Only restricted by system characteristics	• Dependent on system characteristics, but at least as good	40 Sec (Vancouver)	3 Sec	Down to 80 sec
Overlay Capability	N/A	Yes	Yes	Yes	Difficult	Yes
Critical Processing	Smart Wayside	Smart Vehicle	Smart Vehicle & Wayside	Smart Wayside	Smart Wayside/Vehicle	Smart Wayside
Present Status	16 years Phase II operations	Toronto Demonstration - 1996	Toronto Demonstration - 1996	Vancouver System - Operations since 1986 San Francisco Muni - Being deployed	Laboratory Demonstration - Complete 1986	In Test

Table 16. Comparison of M-PRT and Communications-Based Control Systems (page 1 of 2)

System/ Element	Present M-PRT System	MAGGALY MATRA	ULTRABLOK™ HARMON	MICROBLOK™ UNION SWITCH & SIGNAL	SACEM N.G. GEC ALSTHOM
Architecture Description	• Central Supervisory-overall system monitoring & fleet management • Wayside decentralized control of vehicles using point follower strategy • Independent collision avoidance • Vehicle responds to station commands & monitors speed, brakes, on-board status • Open architecture	• Central control manages & regulates movement of train on links & other supervisory functions • Station based unit manages & assures safety of train movements • On-board train unit assures automatic speed control, control & monitors train equipment status • Proprietary architecture	• Central supervisory • Wayside tracks vehicle location • On-board vehicle processor contains functions necessary to support train operation • Open/proprietary architecture to be determined	• Central control facility supervisory functions • Distributed wayside control functions - zone & control location • Vehicle's track their location in control zone • Architecture uses standardized communication protocols	• Central supervisory function • Sector computer control of communication base stations & track side equipment • On-board SACEM computer automatic train control equipment • Architecture design to integrate open interface protocols
Vehicle Functions	• Vehicle Control & Communications System (VCCS), in response to wayside command VCCS generates - Speed, brake, door & switch commands - Responds to wayside FSK messages - Calculates & responds to overspeed condition	• Train determines its own position by on-board unit calculation - Location markers built into transmission line tray - Phonic wheel information - Track characteristic information in on-board unit data base • Calculates distance between location & first fixed or moving obstacle - Adjusts speed or braking	• On-board route profile contains all speed, distance, & object location data. • Utilizes wayside references to update position data • Controls brake & speed in response to profile & target data	• On-board processor - Tracks position - Provides wayside with train length ID & location data - Uses on-board system maps • Updates position based on wayside beacon data • Generates speed profile data from wayside information & Train Inertial Positioning System (TIPS)	• SACEM trainborne computer varies wayside data and communicates with ATC computer and wayside • ATC trainborne computer provides traditional control function and receives data from phonic wheels and beacon sensors • Phonic wheels data determines distance traveled • Wayside beacon sensors update data for location information
Vehicle/Wayside Communications	• Bidirectional inductive coupling through embedded antenna loops • Presence detectors monitor vehicle position	• Transmission line installed in the track - Provides continuous link with trains	• Continuous RF communication of dynamic train data	• Bidirectional leaky coax data radio	• Frequency hopping spread spectrum RF for Toronto demonstration
Wayside Functions	• Station Computer & Station Electronics (SCCS) - Generates vehicle synchronous point follower - Dispatches vehicle to point - Control destination selection faregates boarding displays, concourse display • Guideway Command & Control System (GCCS) - Speed tones, switch tones, FSK messages, stop tones, calibration, presence detection • Collision Avoidance System (CAS) - Safe tone - Switch latch - Disparity detection	• Track sections equipped with wayside control unit - Interrogates each train on cyclic basis & sends obstacle data to following train - Provides to train data on status of track equipment & signal lights	• Distributed controllers that track vehicle location via position reports from trains • Authority targets for any train are issued by controller • Track mounted transponders used as reference marker for vehicle's position update	• Wayside processor - Calculates "virtual" blocks to determine what profile data can be transmitted to train - Knows where other trains or obstacles are located in central zone • Wayside beacons provide position update to vehicle • Wayside processor concurrently with other waysides & control	• Sector computer calculates virtual track circuits, sends data to vehicle and ATC wayside computer, receives and responds to vehicle data • ATC wayside computer provides traditional control functions and receives data from sector computer • Radio base station for communications • Initialization & location beacons
Wayside/Central Communications	• Dedicated land lines	• Land lines	• Land lines	• Land lines, vital serial link between control locations	• Land lines
Central Functions	• MIMIC display • Electrification control • I/O Supervisory control • System status	• Supervisory functions - Power & station control - Management & regulation of train movements	• Supervisory functions - Electrification - System status	• Supervisory functions - Electrification - System status	• Supervisory functions - Electrification - System Status
Headway Design	15 sec	90 sec	Dependent on System Characteristics	30 - 40 Sec	On the order of 90 sec
Overlay Capability	N/A	Yes	Yes	Yes	Yes
Critical Processing	Smart Wayside	Smart Vehicle	Smart Vehicle	Smart Vehicle & Wayside	Smart Wayside
Present Status	16 years Phase II operations	Began Operations 1992	Toronto Demonstration - 1996	In Development	Toronto Demonstration - 1996

Table 16. Comparison of M-PRT and Communications-Based Control Systems (page 2 of 2)

4.3.2.2 Considerations

When evaluating the applicability of railroad communication-based control technology to M-PRT the following are some considerations that need to be taken into account:

- There are fundamental differences between rail transit operations and people-mover operations. For instance, long headways versus short headways.
- There would have to be some tailoring of the railroad system hardware/software to make it applicable to M-PRT, e.g. message traffic capability to accommodate the maximum number of vehicles in a station area.
- M-PRT switching is accomplished on the vehicle and not on the wayside as is done on the rail industry.
- The M-PRT station has multiple berths versus an open train platform.

There is also the basic question of safety, collision avoidance or safe separation, and how these new systems can assure at least the same degree of safety as the present system. In many cases the safety design of the system is of a proprietary nature and can only be assured by the vendor.

Finally, without question, there is a requirement for an up-front systems engineering effort in order to successfully apply any new communication-based train signaling technology to M-PRT.

These and other considerations will be part of the analysis that follows.

4.3.2.3 Potential Impact on M-PRT Interfaces

In order to make a reasonable assessment of the available technologies, some ground rules had to be established to allow apples-to-apples comparisons between systems. To determine the conditions that result in a level playing field for the various technologies, we investigated how any new system would need to interface with the present M-PRT command and control system (C&CS). The interface has to be the same for each new system or comparison data will be useless. Therefore, our analysis assumed that only the control system is different. Where the control system interfaces with some other functional subsystem; e.g. propulsion or brakes; the interface does not change. The present M-PRT C&CS interfaces are shown in figure 9. We then investigated how, on a general basis, these new technologies would impact the C&CS equipment. Table 17 summarizes these impacts.

The assumption that the interfaces would not change allows this analysis to be universally applicable, but in reality there are some M-PRT subsystems that should be changed if a control system upgrade is implemented. In particular, we recommend that the present propulsion controller/brake system design be modified to take advantage of the torque control features of the communication-based systems.

Headway Operations. One of the identified advantages of converting to a communication-based system with its moving block control is the potential for operating with headways shorter than 15 seconds. As part of the Advanced Group Rapid Transit program, Boeing concluded that it would have been possible to safely operate M-PRT with fixed block headways as low as 7.5 seconds. To date, there has not been any compelling reason to operate M-PRT at shorter headways under normal conditions. However, in abnormal conditions such as a series of vehicles stopped on the guideway or an overloaded station such as Medical Center station after football games, shorter headways would allow the system to return to normal conditions faster. With both of these considerations it mind, the communication-based control system could be set to operate at 15 second headways most of the time.

The headways could be reduced to as low as 7.5 seconds as the need arises. Operators will need training for moving block control understanding and usage.

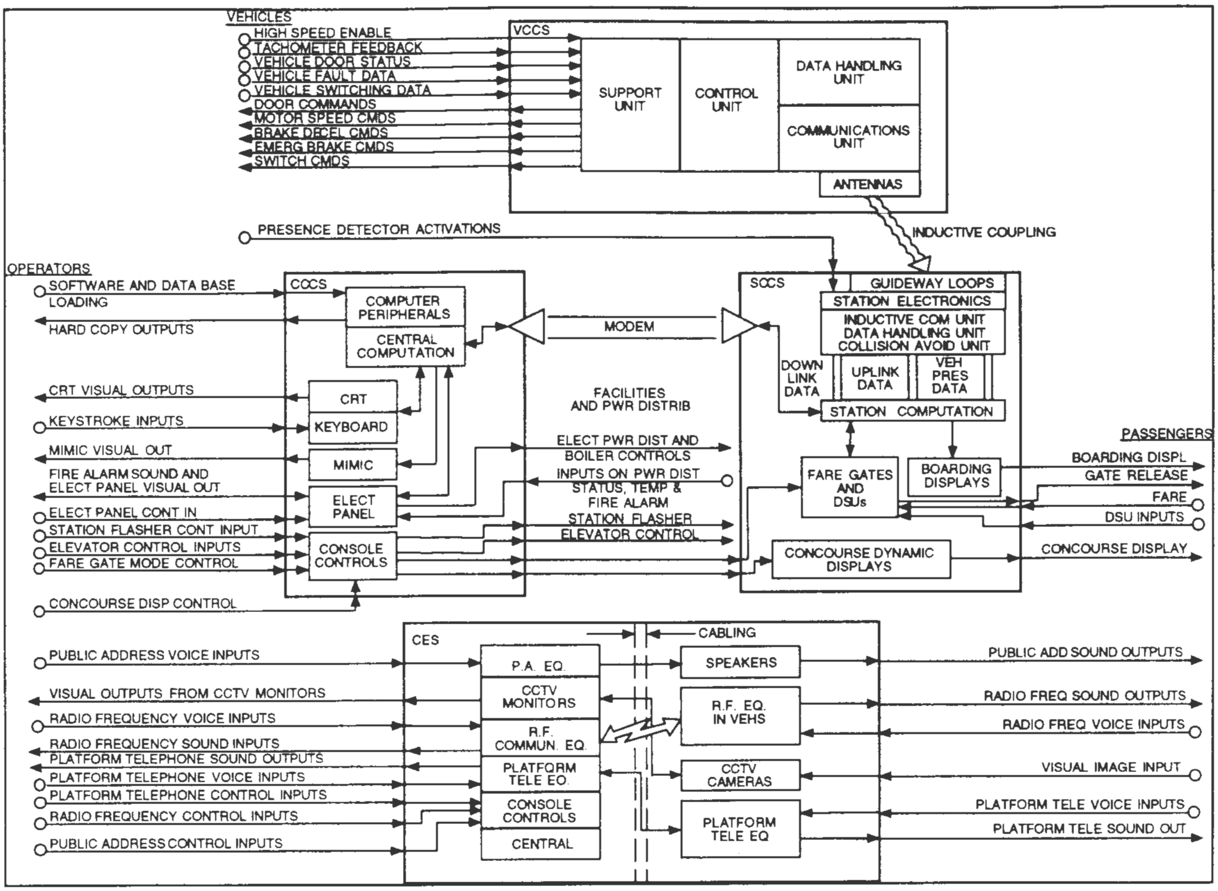


Figure 9. Present M-PRT Command & Control System Interfaces

4.3.2.3.1 Concerns

With an initial idea of where the impacts to the C&CS occur we then addressed our concerns with any application of new technology. There are several important areas of concern that need to be addressed up-front when considering a replacement of the existing M-PRT control system. These include collision avoidance and safety, operability, switching, station stop, headway requirements, overlay potential, control strategy and message traffic.

Collision Avoidance and Safety. A major concern is assuring that the present system safety is not compromised. M-PRT operates with an independent, fixed block, collision avoidance system (CAS)capable of operating with vehicle headways as short as 15 seconds. Communication-based control systems are designed for railroad operations - long headways (90 to 120 seconds) and long train lengths. Is a train system safe-separation calculation applicable to a short headway, multiple vehicle system? The answer to this depends on the design of the new system's safety critical hardware and software. In many cases, this is proprietary information which means that the manufacturer has full responsibility for showing, or at least certifying, that operations with the new technology are at least as safe as present M-PRT operations. In other words, only the supplier knows what is in the design, how flexible it is, and whether or not it could be changed for use in an application for which it was not originally intended. That supplier would have to certify the system safety critical functions for both rail and automated guideway operations.

M-PRT Element	Impact of New Technology
Station Electronics and guideway equipment	Eliminates the requirement for antenna loops and associated equipment. Antenna loops and presence detection are in the same category as railroad track circuits which the rail industry plans to replace with the new communication-based technologies. The present inductive communication system then is replaced by radio or some other communications medium, but the present M-PRT control interfaces remain.
GCCS (Wayside)/Vehicle Messages and Commands	Specific communications with the vehicle depend on the control strategy but, in general: • FSK Messages - new communication-based systems can easily accommodate • Speed Commands - new communication-based systems can easily accommodate • Collision Avoidance - not necessarily a problem with new systems, but is a concern (see below) • Calibration - no problem, the new communication-based systems accommodate vehicle calibration by beacons, markers or some other means. • Stop Command - could be a concern with new technology, (see below) • Switching - could be a concern with new technology (see below)
Presence Detection and Central Control	This depends on the control strategy of the replacing system. Most of these systems use "virtual" maps or "virtual" blocks, and calculate the distance to "obstacles" in the wayside or on-board the vehicle -- they don't require a physical "hit" to assure vehicle position. This gives M-PRT an option to leave the present PD system active to only drive the Mimic board. A better option would be to come up with a new Mimic strategy that doesn't require PD's. Eliminating the PD's is a definite way to reduce maintenance. This scenario also assumes that the new collision avoidance system will not require PD data. (the ODDCAS system is an exception to this). Other Central Control functions such as electrification and station monitor and control can be accommodated by the present equipment.
Vehicle CCS Equipment and Interfaces	Any new system would require replacement of the present vehicle control electronics up to the interface with vehicle operational equipment (propulsion controller, brakes, doors, steering, vehicle status interfaces). The new technologies often require a "smart" vehicle which would require a complete VCCS redesign. Even if the "smarts" were still on the wayside an upgrade of the vehicle electronics is required.
Station Computing	Some of the new systems require station computers, some require zone computers that operate 2-3 stations, and some require a single dual computer to run the entire system. The new systems computer then interfaces with the new communications system.

Table 17. Impacts of Communication-Based Technology on M-PRT System

Operability. While the moving block operations enabled by the communication-based technology theoretically allow headways shorter than 15 seconds, the technology must also provide sufficient vehicle position accuracy. Again, this requires that the supplier scale technology designed for rail application to another application. If the system cannot provide sufficiently accurate vehicle position calculations, the safety system will initiate nuisance shut downs as a result of false unsafe separation reports.

Switching. Railroad switching implements safety critical, interlocked mechanical systems that physically change the track direction by means of wayside equipment. This is one area where M-PRT is radically different from a railroad. M-PRT switches by changing the bias of the on-board vehicle steering as a result of a wayside command. M-PRT may switch right and left, and some switches are hard wired to one direction of travel. The new technology must be able to accommodate vehicle borne switching. This is an important consideration when determining if a new technology can be applied to M-PRT without major modifications.

Station Stop. Another concern is whether or not a train-based design can achieve +/- 6" stopping accuracy at the M-PRT station gate openings. The communication-based control systems are designed for rail applications, which usually have open passenger platforms, rather than the M-PRT multiple gate platforms.

Headway Requirements. Significant changes to the communication-based control system hardware and software may be required to accommodate the short headways. This, is turn, may impact the safety of the system and necessitate recertification.

Overlay Potential. The nature of most of the communication-based control allows them to be tested at Morgantown prior to installation for full-up operations. Most of the systems can be overlaid onto the existing system without interfering with daily operations. However, extra care must be taken if the implementation adds new technology while leaving some of the old technology, such as switching and station stop, in place. During normal MPRT operating hours, the communication-based control system would be turned off and the existing vehicles used. After hours, the new system would be operated with a special vehicle to test vehicle control and verify functionality prior to initiating revenue operations. As an option, operational data, including switching, calibration, speed transitions, and stopping, could be recorded and run against the new system in a simulator.

Control Strategy. Moving block control requires a new operational strategy for vehicle movement. The present point follower control strategy would be replaced with a strategy that is unique to the specific supplier. No matter what strategy (on board maps, virtual blocks, conflict points, etc.) is used, there will be an impact on operability. A detailed analysis is needed to ensure that the resulting operability and trip reliability are as good or better than at present.

Message Traffic. The message traffic for a train based design is not the same as for a people-mover system. Communication-based systems typically are designed for 10-20 trains in a control or station zone. M-PRT may have as many as 40 vehicles within a station area. Any new system would have to handle the maximum expected M-PRT vehicle density.

4.3.2.3.2 Analysis Ground Rules

Using the data developed above, we then incorporated the following ground rules for continuing our evaluation of the new technologies:

a. The present functionality of the M-PRT GCCS must be accommodated by the new system. This includes on-board vehicle switching and stopping accuracy at the platform gate.

b. The Mimic Board function, and other interfacing CCCS functions, must be accommodated by the new system.

c. The VCCS would be replaced by new on-board equipment, but the Vehicle/VCCS interface would not change.

d. The new technology collision avoidance, or safe separation strategy, must be as safe as the present CAS and must be certified by the manufacturer.

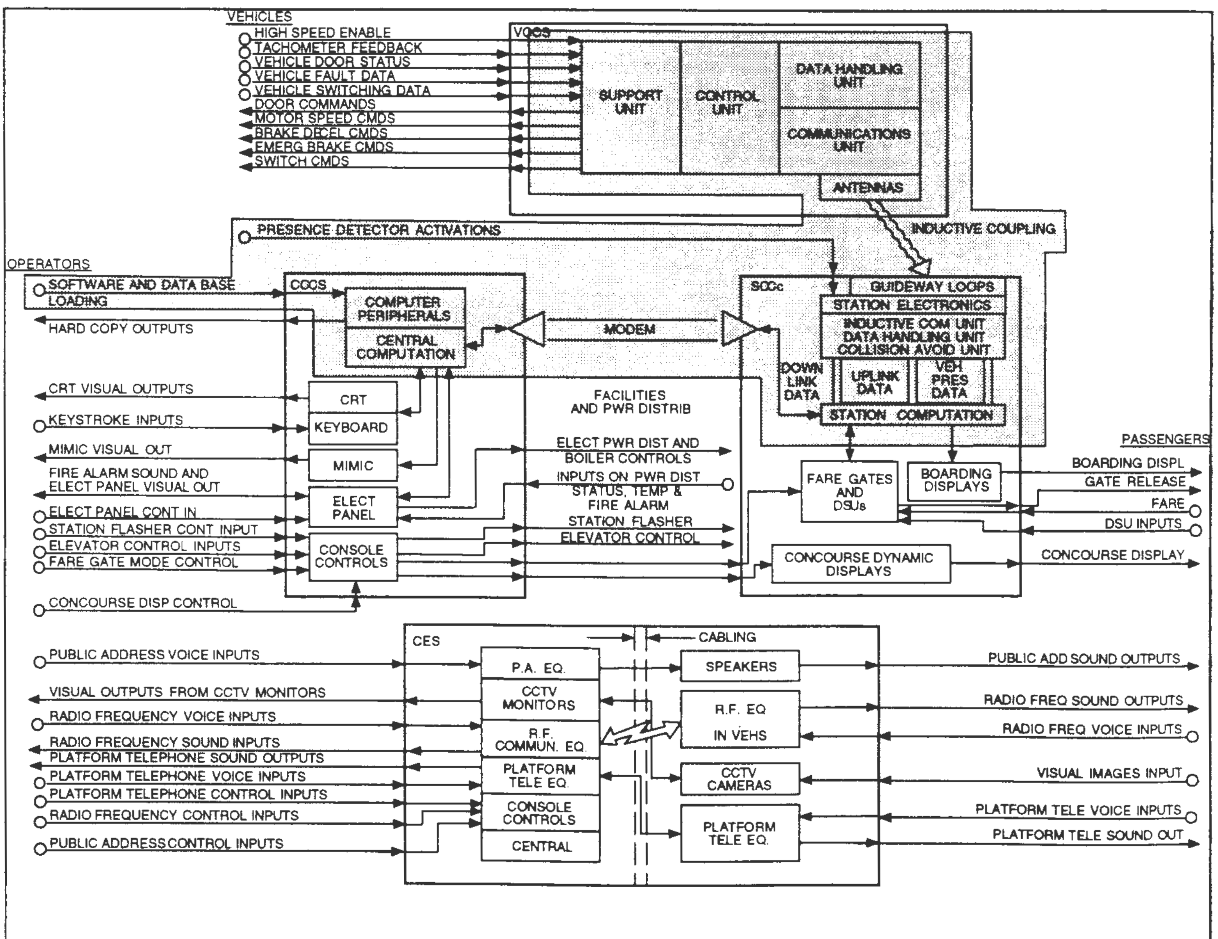
e. Vehicle position accuracy must support the present system operability experience.

f. The new technology must be able to accommodate moving block control down to a minimum of 15 sec headway under normal conditions, with the capability of operations at headways down to 7.5 sec.

g. The new system must be able to be tested and verified by either being overlaid on the existing system, or by simulation using present system operational data.

h. The new communication system must be capable of handling the maximum M-PRT wayside/vehicle message traffic.

These ground rules were discussed with the vendors and there did not appear to be any constraints that would have limited any of the new technology. The application of these ground rules then allows a common control system interface with the present M-PRT C&CS functions as shown in figure 10. The analysis now proceeds to evaluate the specific impacts of new technology on M-PRT operations and maintenance.



The shaded area represents the impact of a communication-based control system on the M-PRT C&CS

Figure 10. New Technology Interfaces With M-PRT

4.3.2.4 Impacts on Operations and Maintenance (O&M).

The analysis of the impact of communication-based technologies on M-PRT operations and maintenance is limited by the availability of firm operational systems data. As has been noted, there are only two communication-based systems for which specific operational data may be obtained, Vancouver SkyTrain (Alcatel) and the Maggaly system (MATRA). The developmental nature of the other alternatives does not allow specific, quantitative comparison data at the present time. Additionally, comparison of the two operational systems with any of the developmental systems requires some subjective opinions as to the operational nature of the developmental equipment. This is not appropriate until the technology has at least been demonstrated.

As a result of this dilemma, we decided to treat the new technology comparison in as general terms as possible, particularly considering how the technology would "fit" into M-PRT. We can do this because:

a. We have established the groundrules as how the new system would be required to interface with M-PRT; and

b. There are similarities in the configurations of these systems that allow this type of comparison. For example, wayside processors and on-board processors come under the general category of microprocessors. The maintenance requirements for microprocessor equipment could be said to be similar for any system. In a like manner, the impact of moving block control on operations should not vary much between suppliers. The largest variance occurs in the wayside/vehicle communication technique and this can be easily pointed out in an a general comparison.

Our analysis then addresses the general impact of new technology to key elements of the M-PRT system which, in turn, impact the overall O&M structure. These key elements are: maintenance concept, system safety, reliability, retrofit requirements, collision avoidance or safe separation, impact on present O&M, and demonstration potential. At the end of this section, in table 18, is the summary of our assessment as to how each of the new technologies would impact the key elements discussed below.

Maintenance Concept. The maintenance concept for any new technology implemented for M-PRT must support the present high system availability. Faults must be detected and isolated in an expedient manner and defective components replaced in the same manner. Requirements for initial spare parts or replaceable line units must be based on availability considerations. New test equipment or fault isolation hardware/software may be required.

The maintenance concept for communication-based control technologies is dependent on the system selected. In general, the candidate systems include the following types of equipment:

• Wayside processors -	Microprocessor equipment
• Onboard Vehicle processor -	Microprocessor equipment
• Wayside/Vehicle communications -	RF based, wayside and vehicle equipment. Leaky Coax, wayside and vehicle equipment Inductive, wayside and vehicle equipment
• Wayside Positioning -	Beacons, Transponders, passive devices
• Wayside to Wayside, Wayside to Zone, Wayside to Central Communications	Modem or LAN equipment

The system selection will determine whether the maintenance is done at the local level or by the supplier. A specific vendor system will, most likely, be serviced by the vendor. The bulk of the equipment, including: radio or leaky coax equipment such as transmitters/receivers and antennas; wayside positioning devices; processors allow removal and replacement by spares at the card or "black box" level. Defective parts can be discarded, returned to the vendor for repair, or repaired locally. Local maintenance would require detailed maintenance data and possibly special test equipment.

The requirements for software maintenance should be included in the maintenance concept. The degree of software maintenance required will be influenced by factors such as the maturity of the selected system, the process and experience of the people that develop it, the flexibility included in the design, and the desire for future functional upgrades. The degree of participation by M-PRT in software maintenance would depend on the selected system and supplier. At present, most of the communication-based control systems contain proprietary software.

System Safety. Any new system installed for M-PRT must be as safe as the present system. The assurance of this safety requirement can be accomplished in at least two ways

a. Fault tree and hazard analysis data provided by supplier.

b. Certification of compliance by supplier.

The method to be used depends on the proprietary nature of the supplier's safety system.

Reliability. The application of new technology should result in an improvement over the present reliability experience of the M-PRT GCCS and Station Control and Communication System (SCCS.) The inherent reliability of new microprocessor, or computer hardware, should decrease the probability for the critical failures that currently stop vehicle operations. The new systems incorporate redundancy in their designs to further enhance reliability. Specific data can only be obtained from the suppliers and this will depend in a great part on upcoming test and demonstration programs.

Retrofit Requirements. The installation of new control technology at M-PRT will result in the following general retrofit requirements. Some of the requirements will be specific to the system selected.

General Requirements:

Vehicle Control Unit -	Remove and replace present VCCS in all cases. Install antennas on vehicles.
Wayside Processors -	Remove and replace existing station electronics in all cases. May require removal and replacement of existing station computers. Requires, at a minimum, an interface with the existing station computer for boarding display, fare gate, and DSU operation.
GCCS, loops, PD's -	Abandon or remove, if desired, for all systems but ODDCAS.
Central Control	Requires new interface and computation method for Mimic Board. May require new Mimic Board. Central computers and wayside (station) communications depend on the specific system selected. Most of the new systems use dedicated land lines.

System Specific Requirements:

Wayside Positioning-	Requires installation of beacons, transponders or other devices.

Wayside/Vehicle Comm-Requires installation of one of the following

- Radio base stations, radio antennas
- Leaky coax installation
- Inductive Comm loops - single
- Inductive Comm loops - multiple

Software- M-PRT software must be modified to disable functionality that will be replaced by new system. New software must interface with present software where required.

Wayside/Central Comm-May require new modem or LAN equipment.

Collision Avoidance or Safe Separation. This element is related to System Safety above. The new technology collision avoidance is to be as safe as the present independent fixed block system. The calculation for collision avoidance or safe separation may be made (1) within the wayside processor, (2) within the vehicle processor, or (3) within some combination of wayside and vehicle processing.

Impact on Present O&M. Implementation of new technology should reduce the amount of maintenance required by the M-PRT system while improving operations.

The new technology would replace equipment that is becoming obsolete and may be unserviceable in the future. Elimination of the present antenna loops, PDs, and associated electronics further reduces maintenance requirements.

If the new technology is implemented, there will be a change in the required maintenance skills. The majority of new systems require radio communications equipment, and some suppliers that are presently using leaky coax, or inductive loop technology, are leaning toward RF. Spread Spectrum RF is the leading candidate for vehicle/wayside communications. There is a real possibility that new test equipment will be required.

Demonstration Potential. The new control systems, with the possible exception of ODDCAS, can be overlaid on the existing M-PRT system without interfering with present operations. Some of the systems require leaky coax or long inductive loops, but this cabling can be laid on the guideway surface.

Test or demonstration equipment could be installed on a section of guideway and run in parallel operations with the present control system. A special test vehicle, along with the wayside equipment would be necessary. This would allow verification of the new control system prior to implementation. Similarly, a simulator test bed consisting of new technology equipment could be set up and run against taped data of actual M-PRT operations.

There are a number of scenarios that could be implemented to take advantage of this overlay capability. If actual operations with the new technology were to be demonstrated, they could be accommodated by overlaying and operating on an M-PRT end segment: Towers - Medical Center or Beechurst - Walnut. M-PRT is unique in that it provides the capability of a test bed for new technology, and the technologies to be tested do not necessarily have to be control systems.

ELEMENT	AEG FLEXIBLOK™	GRS ATLAS™	SELTRAC ALCATEL	BOEING (AGRT) ODDCAS	AATC (BART) HMK	MAGGALY MATRA	ULTRABLOK™ HARMON
Maintenance Concept	• Presently not specifically defined. It would be assumed that equipment would have fault detection capabilities and replaceable components.	• Presently not specifically defined. It would be assumed that equipment would have fault detection capabilities and replaceable components.	• Not specifically defined for Toronto demonstration system, but it would be assumed that -- would have fault detection capabilities and replaceable components	• Similar to present M-PRT maintenance concept	• Not specifically defined but assumed that equipment would have fault detection capabilities and replaceable components.	• Maintenance concept is known and presently is use on system	• Presently not specifically defined, assumed that equipment will have fault detection capabilities and replaceable components
Initial Cost	• Presently not known, could be assumed to be similar to cost of a track circuit implementation	• Presently not known, could be assumed to be similar to cost of a track circuit implementation	• System have been deployed and data is available (Vancouver). San Francisco Muni system is presently being deployed	• Equal to the installation cost of present inductive comm system, plus hardware and software adaptation costs.	• Presently not known, could be assumed to be on the order of implementation cost for track circuits	• System has been deployed, (MAGGALY) data is available	• Presently not known, could be assumed to be on the order of implementation costs for track circuits
Life Cycle Cost	• Cannot be determined at present, yearly O&M costs are not known.	• Cannot be determined at present, yearly O&M costs are not known.	• Vancouver system have been deployed and data is available	• Cannot be determined a present, yearly O&M costs should not exceed present costs	• Cannot be determined at present, yearly O&M costs are presently not known	• Some data is available, system has been in operation since 1992	• Cannot be determined at present, yearly O&M costs are presently not known
Safety	• Proprietary safety system design makes use of vital computers. • Provides basic safety function for automatic train protection	• Proprietary safety system • Incorporates fault detection and fault recovery in design • Uses numerically integrated safety assurance logic	• Proprietary safety system uses redundant on-board processors, vital wayside control units	• Uses checked redundancy to assure safety • Extensive analysis to assure software safety • Safety functions shared between vehicle wayside	• Vital computers continuously cross check and are redundant • Triplex parallel microprocessor for train control • Fail safe design philosophy • Cyclic redundancy check (CRC)	• Proprietary safety system • Uses "Coded Processor" safety principals • Single processor uses cyclic checking • Has station safety devices to protect passengers	• Proprietary safety system • Uses vital computers
Reliability	• Presently not known, may be assumed to be similar to other microprocessor based equipment.	• Presently not known, may be assumed to be similar to other microprocessor based equipment. • System uses redundant to enhance reliability and availability	• Data is available from operating systems (Vancouver)	• Should be equivalent to present M-PRT experience	• Presently not known • System uses redundancy	• Uses redundancy to enhance system reliability • System is designed to be fault tolerant	• Presently not known
Retrofit Requirements	• Vehicle control unit, wayside, guideway passive equipment, control software interfaces with M-PRT	• Vehicle control unit, wayside, guideway passive equipment, control software interface with M-PRT and control software	• Vehicle control unit, wayside processors, guideway passive equipment, guideway inductive comm loop, control software and control software interface	• Vehicle control software, guideway loop removal and replacement with ODDCAS loops & P.D.'s, vehicle control unit replacement, control software	• Vehicle control unit control, software wayside equipment - antennas & radios, control software and control software interfaces	• Vehicle tachometers would be changed to phonic wheels, transmissions can be radio or inductive, control software, interface with M-PRT, MIMIC	• Vehicle control unit, wayside processors, control software, interfaces with M-PRT, MIMIC
Collision Avoidance	• Calculates "Virtual Occupancy" and "Conflict points"; speed and braking control is determined on board vehicle and control software	• Vehicles have infrastructure and vehicle parameter data to determine distance to obstacle • Wayside reports obstacles to vehicle and tracks vehicle	• Wayside monitors vehicle positions and vehicle-to-vehicle headway • Vehicle responses to wayside commands	• Similar to present system but uses ODDCAS loops for determining safe separation for moving block operations	• Wayside determines train position based on RF propagation time, determines location of other trains in system and issues speed and brake commands to trains	• Vehicle calculates position and distance to fixed or moving obstacle • Wayside provides obstacle data to vehicle	• Vehicle calculates and controls brake and speed in response to location of target data • Wayside updates target data and transmits to vehicle
M-PRT O&M Impact	• Training necessary for use of new equipment - operations and maintenance. • May require new test equipment	• Training necessary for use of new equipment. • May require new test equipment	• Training necessary for use of new equipment. • May require new test equipment	• Training necessary for new operations • Maintenance methods should not change	• Training necessary for new operations • New equipment to support RF system • Training necessary for RF equipment maintenance	• Training necessary for new operation • New vehicle equipment - phonic wheels • Maintenance of transmission system • New test equipment	• Training necessary for new operation • RF communications requires new skills • May require new test equipment
Demonstration Potential	• Can be overlaid on present system	• Can be overlaid on present system	• Can be overlaid on present system	• Difficult to overlay • System has been simulated in laboratory	• Can be overlaid on present system	• Can be overlaid on present system	• Can be overlaid on present system
Risk	• Risk areas are - Application - Technology - Maturity - Approach	• Risk areas are - Application - Technology - Maturity - Approach	• Risk areas lessoned by having operational data, but risks are - Application - Technology - Maturity - Approach	• Risk is in implementing 1980 technology, even if based on M-PRT design • Uses multiple inductive communication loops • Risk areas are - Application - Technology - Maturity - Approach	• Risk areas are - Application - Technology - Maturity - Approach	• Risk areas are lessened by having some operational data, but risks are - Application - Technology - Maturity - Approach	• Risk areas are - Application - Technology - Maturity - Approach

Table 18. Projected Impact of New Technologies on M-PRT Operations (page 1 of 2)

ELEMENT	MICROBLOKâ UNION SWITCH & SIGNAL	SACEM N.G. GEC ALSTHOM
Maintenance Concept	• Presently not known, could be assumed to be on the order of implementation costs for track circuits	• Presently not known, could be assumed to be on the order of implementation costs for track circuits
Initial Cost	• Presently not known, could be assumed to be on the order of implementation costs for track circuits	• Presently not known, could be assumed to be on the order of implementation costs for track circuits
Life Cycle Cost	• Cannot be determined at present, yearly O&M costs are presently not known	• Cannot be determined at present, yearly O&M costs are presently not known
Safety	• Proprietary safety system - makes use of LA Green Line experience	• Proprietary safety system
Reliability	• Presently not known	• Presently not know • System makes use of existing track circuit hardware to maximum extent possible
Retrofit Requirements	• Vehicle on-board processor, leaky coax radio equipment, wayside processors, guideway beacon equipment, control software and interfaces with M-PRT, MIMIC	• Vehicle on-board processor, vehicle phonic wheels, wayside processor, guideway beacons, control software and interfaces with M-PRT MIMIC RF spread spectrum communications
Collision Avoidance	• Vehicle tracks position by means of on-board maps and provide wayside with position data • Wayside processes "Virtual" blocks and transmits obstacle data to vehicle	• Vehicle position reporting to wayside, uses phonic wheel data for position and location • Wayside calculates virtual track circuits and reports data back to vehicle
M-PRT O&M Impact	• Training necessary for new operations • Skills for leaky coax radio maintenance • May require new test equipment	• Training necessary for new operations • New RF spread spectrum radio maintenance • May require new test equipment
Demonstration Potential	• Can be overlaid on present system	• Can be overlaid on present system
Risk	• Risk areas are - Application - Technology - Maturity - Approach	• Risk areas are - Application - Technology - Maturity - Approach

Table 18. Projected Impact of New Technologies on M-PRT Operations (page 2 of 2)

(This sheet left intentionally blank.)

4.3.2.5 Risk Assessment.

The implementation of any new technology involves risk. The risk is assessed by knowledge of factors that are the result of careful analysis and: experience with system hardware and software; operational experience; reliability and maintainability experience; cost of implementation; and cost of O&M. Communication-based control system technology is so new that very little risk assessment information is available. This forces an assessment of M-PRT risk to be based on factors other than traditional. The following assessment considers the risk to M-PRT of implementing any of the alternatives focusing on the present state of communication-based technology development.

a. **Application.** The present systems are being developed for railroad industry application, not for people mover application. M-PRT application will require some changes in the software being developed. Hardware changes are not obvious at present and may be minimal. The changes necessary for M-PRT cannot be specifically quantified at this time. Any changes to production hardware and/or software represents a moderate-to-high risk factor. The ODDCAS system is an exception because the M-PRT system was used for its design baseline.

b. **Maturity.** M-PRT adoption of a new control technology requires maturation of the present systems, the majority of which are in a development/test phase. This maturation will determine how many of the present systems will actually be available to M-PRT. The degree of acceptance of these technologies will be determined by the market forces of the rail industry. As a result, there is be a high risk in recommending any particular system at the present time. The question then becomes one of when this maturation may happen. It is the opinion of the Managing Editor of *Railway Age* that this weeding out process will take 4-5 years.

c. **Technology.** Selection of a particular system means selection of a particular communication technology - RF, leaky coax, inductive. There are particular advantages to each, but there are risks involved in selecting any specific offering at present. RF communications has many distinct advantages, but little application experience. Inductive communications have operational experience in the transit industry, but have disadvantages when compared to RF. Again, it is too early to try to trade off advantages and disadvantages.

As part of risk mitigation, an up-front Systems Engineering study must be performed to determine the operational requirements for any new control system being suggested for M-PRT. One cannot recommend a certain system based on intuition, technology, or cost alone. The application of a systems approach reduces the selection risk by identifying the tradeoffs that may be required regarding headway, maintainability, costs and other system factors. This then allows a rational comparison between the technologies available.

4.3.2.6 Implementation and Cost

The analysis addressed the actions necessary to implement any new technology for M-PRT and the costs associated with these actions.

Implementation. The time frame suitable for implementation of a communication-based control system at M-PRT depends on the actions of the rail market to assess and settle on the technology that best suits the industry needs. Assuming this takes five years, a conservative implementation time-line for M-PRT would look like the following.

Systems engineering study and specification *

• Technology definition available, start engineering application study	Jan. 2001
• Engineering application of applicable technologies to M-PRT bid package	June 2001 - complete
• Out to bid (control system contract)	Aug. 2001
• Bid opening and award	Oct. 2001
• Preliminary design review	Apr. 2002 - complete
• Critical design review	Aug. 2002 - complete
• Hardware and software development	Feb. 2003 - complete
• In-plant testing and overlay testing complete	May 2003
• Start M-PRT retrofit	June 2003
• Retrofit and final system testing complete	Dec. 2003

* The up-front systems engineering study can be performed at any time. The length of this study is estimated to be six months.

Initial Cost. Because seven of the nine systems are presently in development, any cost data is very speculative. There is not yet enough information on all the technologies to quantify a conclusive cost for implementation. In a conversation with BART, it was noted that a rule of thumb used for track circuit cost, $1 million/mile for a rail application, might be applicable. The implementation of a communication-based system is similar in task structure to what is necessary to implement a track circuit system. Both systems require engineering, manufacturing, test and implementation of a control system. The $1 million/mile rule of thumb for rail application covers planning, hardware, basic vendor software, system engineering, inplant test/engineering, and installation. This may be low for M-PRT since there are fewer miles of track over which to distribute the engineering costs. In addition, there is an unknown cost associated with adapting a railroad based design to people-mover requirements. This customer application engineering could add as much as 50% to the costs, especially if changes are required in the software design and retesting and recertification are necessary. While M-PRT is by no means a rail application, this rule of thumb is all we have to work with at this time. On the surface, $1 million/mile appears to be reasonable for a system retrofit. However, this figure will be significantly affected if a large amount of software development is required.

At this time, we cannot say whether or not any particular communication-based technology has a cost advantage over the others. The complement of computers and communications electronics for the various communication-based systems is roughly the same when applied to M-PRT. Installation of a leaky coax or a long loop inductive communication system may appear to be more expensive than installation of an RF system, but communications equipment will be less expensive.

The initial cost must include the systems engineering effort necessary to adapt the new technology to the present M-PRT system. This effort would include allocation of operational requirements to a specification and the identification of interface requirements for hardware and software. It must also consider the testing necessary to verify the system requirements. The system engineering effort may be done by an organization other than the supplier.

Life Cycle Costs. As with initial costs, life cycle costs are presently indeterminate because of the state of technology development. Determination of future costs. The life cycle costs would be made up of:

- Initial Costs - Includes procurement, installation, retrofit of existing equipment, spares provisioning, and new maintenance equipment. Includes effort for any applications engineering such as systems engineering, software engineering, testing drawings, manuals, and training.
- Recurring Costs - These are the annual costs for operations and maintenance of the new system. The assumed life of any new system would be twenty years.

Recurring costs cannot be specifically addressed because of the developmental nature of the majority of the new control technologies. There is also risk in using the operating systems data: The Alcatel system has been in operations since 1986; the Maggaly system went into operations in 1992. This old/new mix makes data comparison risky. Maggaly data would probably most representative of the new technologies, but this is a single data point.

Cost Estimate

Based on the above, the following for information-only estimate is offered as an approximate initial cost for new control technology implementation.(1996 dollars)

• Basic engineering, hardware, software, test, installation 8 miles x $1 million/mile =		$ 8 million
• Customer Application Engineering		$ 4 million
	Subtotal	$12 million
• Cost Uncertainty @ 30%		$ 4 million
	Total Cost	$16 million

4.3.2.7 Conclusions

The analysis of new communication-based technologies alternatives and their potential for application to M-PRT leads to the following conclusions.

a. The railroad industry has provided M-PRT the means to modernize and enhance operations/maintenance by implementing a communication-based control system. It will be the railroad industry that ultimately defines which system, or systems, will be available to M-PRT.

b. It is 4-5 (or more) years too early to make a definitive recommendation as to which new technology would best suit M-PRT. Test and demonstration of proposed systems is a near term action and specific data will be forthcoming in the near future.

c. Even though there are two systems from which operational data is available, neither of these systems use the latest RF communications technology which may offer significant advantages. The basis for any recommendation requires data on all technologies.

d. There are unknowns related to the application of a railroad oriented control system design to a people-mover system. These unknowns can only be evaluated when system requirements and control system data are available.

e. It is not too early for M-PRT to begin the Systems Engineering that would derive up-front requirements for new technology. The requirements for headway, safety, reliability, maintainability, and interfaces, could be established and available for future application.

5. TEST APPROACH

Testing of the rehosted software in the laboratory and on-site is a key part of the upgrade effort. We recommend use of an incremental approach:

- Executive
- Executive with each program (CAP, PSAP, MSAP) individually
- Executive and CAP with simulator
- Executive, CAP and each individual station with simulator.

If a problem exists in the interface between station and central, the stations can also be tested with a simulated central.

We recommend that M-PRT operators be involved in the final increment of laboratory testing. This would allow them to become familiar with the new system and would also let them experience software reactions to anomalies that would not normally occur during operations.

Figure 11 shows a concept for the system integration laboratory (SIL) configuration. A station computer and the dual central computers are shown, along with a computer hosting an environmental simulator. In any one test, the simulator will represent the elements of the system that are not present, such as the guideway, vehicles, remaining stations, and central if it is not under test. This approach was successfully used in Phases IB and II of the M-PRT development.

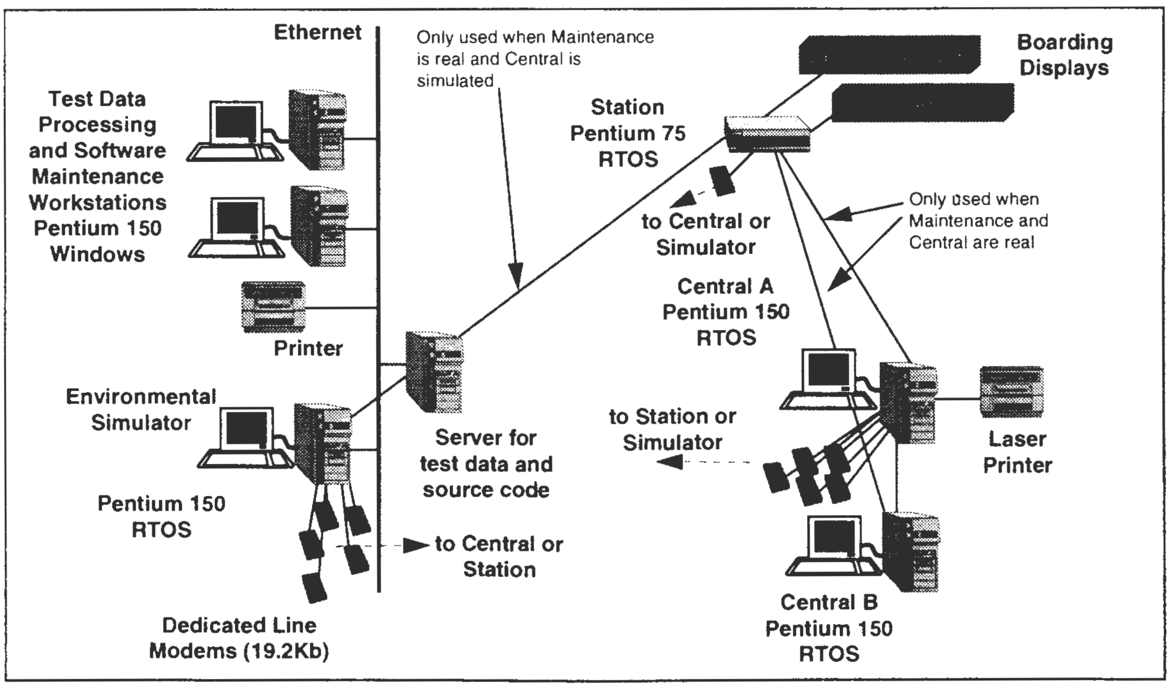


Figure 11. Laboratory Test Configuration

After all tests have been run successfully in the laboratory, the system will be ready for installation and testing in Morgantown. On-site tests should verify that all functions that were tested in the laboratory work using the real system. Our concept is for a contractor test director and engineering personnel to be on-site, but the tests would be run by M-PRT operators. Again, we recommend an incremental approach:

- Install and checkout the new computer equipment and the interfaces to the station electronics and mimic board. Verify communications between all stations and central.
- Verify station software can be downloaded properly
- Run central standalone tests.
- Run central with the stations and one vehicle.
- Run central with the stations and two vehicles.
- Run central with the stations and many vehicles.

5.1 Test Procedures

The test descriptions and procedures that were used for Phase II testing are extensive and can be used for the computer upgrade laboratory testing activity with few modifications. These documents, listed in table 19, cover all station and central functions, individually and as an integrated subsystem. A brief review of the procedures shows that minor modifications are required to accommodate the computer system architecture differences. These, and changes needed to accommodate new or revised functionality, should be incorporated as part of the computer upgrade. In addition, the contractor and customer should review the procedures to determine if any areas need additional emphasis. For example, a test representing the conditions at Medical Station after a football game should be added.

D191-94510-1	Computer Program Test Description - Central Applications Program
D191-94511-1	Computer Program Test Procedures - Central Applications Program
D191-94519-1	Computer Program Test Description - Station Software
D191-94520-1	Computer Program Test Procedures - Station Software
D191-94555-1	Computer Program Test Description - MPRT Software Subsystem
D191-94556-1	Computer Program Test Procedure - MPRT Software Subsystem

Table 19. Reusable Test Documentation

A second set of test procedures will be required for on-site testing. We recommend that these procedures be versions of the SIL test procedures that have been adapted to use real, rather than simulated, equipment.

5.2 Environmental Simulation

The Environmental Simulation was a key element in the successful transition from the Phase IB to the Phase II system. It allowed all software functions to be tested in the system integration laboratory (SIL) at the Boeing facility, minimizing the cost of field installation and test. As shown in figure 12, tests were pre-scripted using the Scenario Pre-Processor program. Scenario files were fed into the environmental simulation. It ran in real-time and interacted with one or more operational software programs.

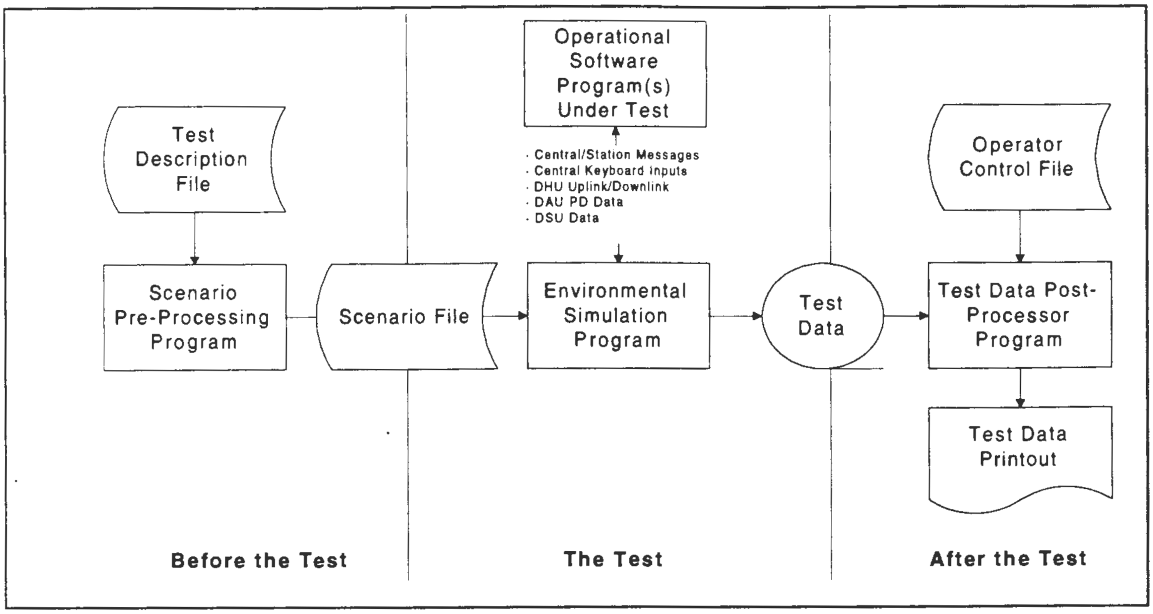


Figure 12. Phase II Simulator Software Subsystem Concept

Although the Phase II simulation was implemented using Data General Eclipse assembly language, the design was transportable and is thoroughly documented using program design language (PDL). This design can be implemented in the selected high order language, and use the real-time operating system that is selected for the operational software. In our upgrade concept, the Scenario Pre-Processor and Test Data Post Processor will be developed and run using a commercial product such as Microsoft Visual C++™ running under Microsoft Windows ™. Scenario files and test output data will be stored on a file server that can be accessed by the Environmental Simulator as well as the Scenario Pre-Processor and Test Data Post Processor. Table 20 shows the estimated size of the three elements of the simulation subsystem if no additional features are added.

	Existing LOC		Lines	Ratio Existing	LOC
Software Element	Assembly	FORTRAN	Replaced by OS	to Future	After Rehost
Pre-processor	76	1168	0	1 to 1	1244
Simulator	10,763	0	2400	3 to 1	2788
Post-Processor	2763	0	0	3 to 1	921
Total	13602				4953

Table 20. Estimated Size of Rehosted Simulation Subsystem

While the existing simulation design could be used as is, we recommend that a further investigation be included in the actual upgrade. The objective would be to take advantage of the vast improvements in computer hardware and software to improve the efficiency of the software subsystem test activities. Things to be considered include:

- Use of any simulation tools that may be available with the real-time operating system to replace functions currently in the Environmental Simulation program.
- Simulation of the mimic board
- Incorporation of additional features into the Environmental Simulation that would perform real-time analysis and eliminate some or all of the Test Data Post Processor.

6. COST AND SCHEDULE

6.1 System Configuration

We developed cost and schedule estimates for the M-PRT system computer upgrade based on the following configuration:

- Pentium (X86) platforms with a dual Central computer and single station computers
- VXWorks real-time operating system
- Automated translation to ANSI C programming language compiled using a C++ compiler

The baseline software configuration consists of the existing code rehosted to run using the new computer platforms. The Executive is replaced by the real-time operating system except for the functions that were identified in section 4.2.4. CAP and PSAP require new code to drive the programmable boarding display and to implement circulation mode. We have not identified any design changes required for MSAP.

Table 20 shows the number of lines of code that will exist after the rehost, as projected from the existing lines of code. The conversion ratio of existing lines of PDP11 assembly language code to C is based on manual recoding of a small sample of M-PRT modules. The figures in table 21 were input into the COCOMO model[7], to estimate software rehost cost and schedule. The COCOMO spreadsheets are shown in Appendix C.

Software Element	Existing LOC Assembly	FORTRAN	Lines Replaced by OS	Ratio Existing to Future	New LOC	LOC After Rehost
MSAP	650	0	0	1 to 1		650
CAP	8080	1360	0	1 to 1	500	9940
PSAP	4450	0	0	1 to 1	100	4550
EXEC	13,740	0	13340	1 to 1	500	900
Subtotal	26920					16040

Table 21. Estimated Source Lines of Code

6.2 Schedule

We estimate that it will take 15.5 months from contract award to completion of system test to upgrade the M-PRT computer hardware and software. This flow time allows for design reviews with the customer and extensive testing both in the laboratory and at Morgantown. As shown in figure 13, a start in mid-April of 1997 enables the upgraded system to be operational in early August 1998.

[7] Barry W. Boehm, Software Engineering Economics

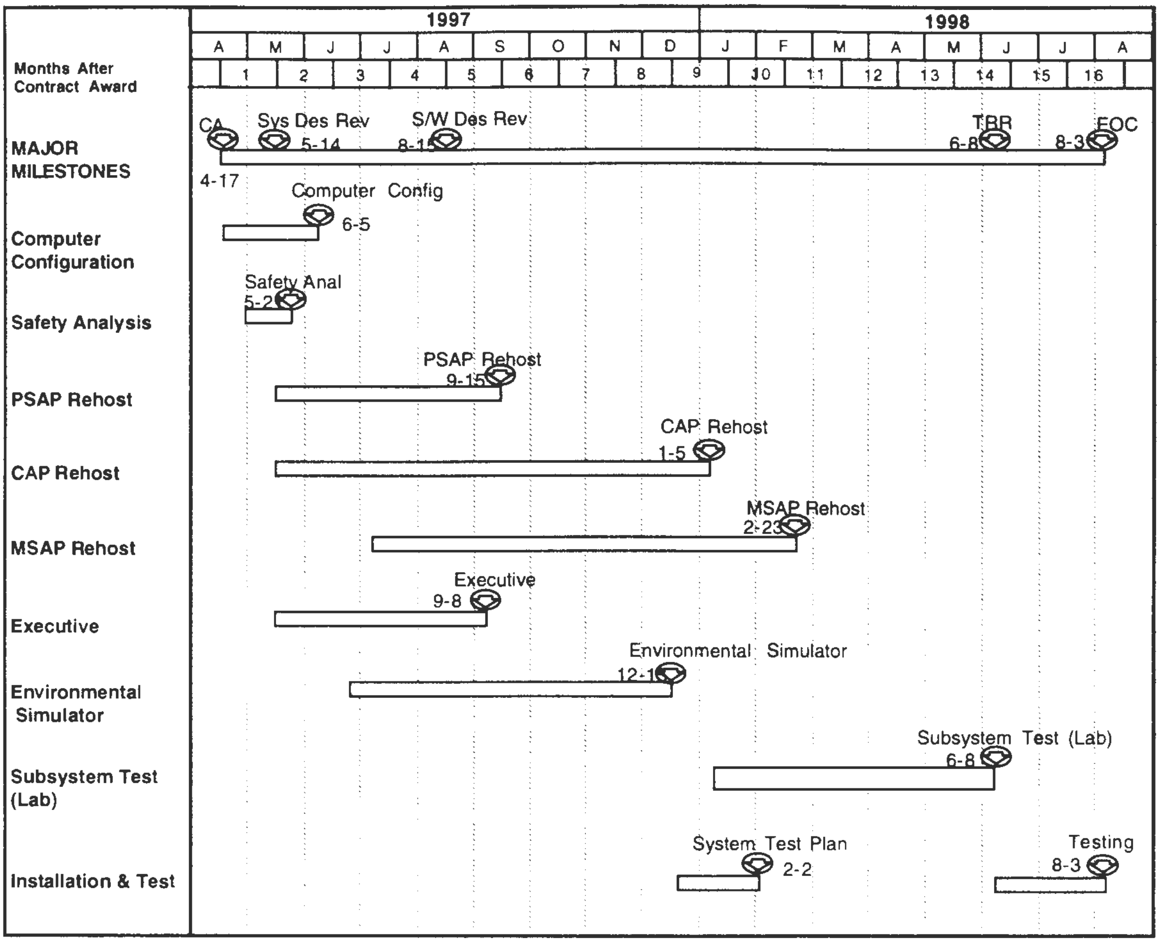


Figure 13. Upgrade Schedule

6.3 ROM Cost

Assuming the baseline configuration defined in 6.1 and the schedule shown in 6.2, we have offer the following rough order of magnitude (ROM) cost. This ROM is expressed in "then year" dollars and is to be considered "for information only."

Labor, material, and travel	$3,393,769
Profit	659,007
Contingency	1,215,833
Total	$5,268,609

Activities included in the estimate are described below. Appendix D contains a draft statement of work for the computer upgrade program.

6.3.1 Computer Platform Upgrade

a. Develop a computer system architecture that uses Intel X86 computer platforms to replace the existing Digital Equipment Corporation (DEC) PDP 11 computers and the special purpose equipment that interfaces the computers with other electronics at the stations and central.

b. Perform an analysis to verify that the new computer system mean-time-between-failures exceeds 1221 hours, the best performance experienced by the present dual system through 1995.

c. Identify the quantity of spare parts required to maintain or exceed the highest level of computer system availability achieved through 1995

d. Provide computer installation drawings for station and central.

6.3.2 Safety and Operability Analysis

Perform an analysis to verify that the computer system upgrade does not negatively impact safety and operability.

6.3.3 Operational Software Rehost

a. Select one of the three operating systems for procurement based on the available features, tools, contractor experience with the operating system, and life cycle cost.

b. Review the existing design documentation and update it to reflect changes to the computing system configuration, including operating system.

c. Design changes required to incorporate circulation mode and programmable boarding displays into the applications software.

d. Conduct a design review with the customer.

e. Translate the existing code into ANSI C high order language, review against the updated design, and implement any required changes.

f. Update the test descriptions and test procedures for consistency with the computing architecture and software design changes.

g. Perform unit testing of the rehosted software.

h. Develop the tools required to integrate and test the rehosted software including a real-time simulation, scenario pre-processor, and post-test data processor.

i. Integrate and test the rehosted software. Perform comprehensive testing of the upgraded system at the contractor facility prior to installation at WVU.

j. Update and prepare electronic versions of the following M-PRT documents: Software Requirements Specification, Operational Software Design Description, the Computer Program Development Specifications (Part 1's,) Operational Software ICD, the Structure and Content of the Data Bases, computer program test descriptions, and computer program test procedures.

k. Revise pages of the Computer Program Product Specifications as required.

6.3.4 Drawings and Data

a. Prepare interface drawings for each unique configuration.

b. Prepare procurement specifications for the processors and interface equipment.

c. Prepare procurement specifications or drawings for station electronics/computer interface cables.

d. Prepare installation drawings for the computer hardware at each station and central.

6.3.5 System Test Planning

a. Develop system test plans and procedures and coordinate them with WVU personnel.

b. Conduct a Test Readiness Review on completion of integration and test at the contractor facility.

6.3.6 Installation and Test

a. Coordinate the installation schedule with WVU for approval.

b. Direct the activities of technicians to be provided by WVU to remove and dispose of the existing PDP11 computers and displays, special purpose equipment and associated cabling.

c. Direct the activities of technicians to be provided by WVU in the installation and checkout of the new computers and associated cabling. This installation and checkout will include power on, diagnostics, and inter-computer communications checkout to assure that the installation is ready to proceed with system test.

d. Load the rehosted software and verify basic functionality.

e. Direct M-PRT operators in the conduct of system tests to confirm operational integrity prior to passenger carrying operations.

f. Diagnose and correct any problems with the computer system hardware or software that may be discovered during system testing.

6.3.7 Procurement.

a. Procure all equipment and spares required for the computer system upgrade (does not include programmable boarding display hardware.)

b. Procure station electronics/computer interface cables.

c. Procure the operating system, development environment, and support licenses necessary to support development and complete testing of the upgraded system (does not include source code license.)

6.3.8 Commercial Manuals

a. Determine commercial operations and maintenance manual requirements and coordinate them with WVU.

Procure the manuals and deliver to WVU

7. CONCLUSIONS AND RECOMMENDATIONS

Computer Platform. Although any of the three platforms that we investigated could perform the job adequately, we recommend the x86 architecture as the platform for the M-PRT computer upgrade. This recommendation is based on the architecture's widespread use worldwide, its history of backward compatible upgrades, and the multitude of reputable vendors. We recommend using single high reliability single-board computers at the stations and dual Pentium workstations at Central. Even without dual station computers, the predicted availability for this configuration is more than 10 times the M-PRT requirement. With the single station computers, the functionality currently performed by the SPE is greatly simplified and can be handled by personality modules that plug into the X86 platforms.

Operating System. We evaluated six real-time operating systems and found that none of them clearly stands out over the others as the best choice for the M-PRT upgrade. The technical capabilities are approximately equivalent for most of the systems and they all have integrated development tool suites. To maximize the likelihood that the OS will be supported for the next 15 to 20 years, we recommend choosing one of the systems with the largest market share such as VXWorks from Wind River Systems or pSOS from Integrated Systems, Inc. Since the operating system procurement cost is insignificant in relation to the cost of rehosting the software and its maintenance cost is small relative to other M-PRT operations and maintenance costs, price will only be a significant factor if everything else is equal. The consideration that may end up driving the decision is contractor experience with the candidate operating systems. Therefore, we recommend that the selected upgrade contractor make the final operating system selection based on the experience of its personnel and the OS capabilities and tool sets available at that time.

High Order Language. For the M-PRT computer software rehost, we recommend use of the ANSI C programming language. Translation from PDP11 assembly language to C is reasonably straightforward and a first-cut can be generated using an automatic translator. If we were starting from scratch to build a control system for the M-PRT system or if a significant number of design changes were required, then Ada would be our preferred choice of high order language.

Test. Testing of the rehosted software in the laboratory and on-site is a key part of the upgrade effort. We recommend use of an incremental, scenario-driven test approach using a real-time environmental simulator in the laboratory. We suggest that M-PRT operators be involved in the final increment of laboratory testing. This would allow them to become familiar with the new system and would also let them experience software reactions to anomalies that would not normally occur during operations. To minimize cost and operator training time, on-site testing should be performed by the M-PRT operators with contractor support.

New Control System Technology. The analysis of new communication-based technologies alternatives and their potential for application to M-PRT leads to the following conclusions.

a. The railroad industry has provided M-PRT the means to modernize and enhance operations/maintenance by implementing a communication-based control system. It will be the railroad industry that ultimately defines which system, or systems, will be available to M-PRT.

b. It is 4-5 (or more) years too early to make a definitive recommendation as to which new technology would best suit M-PRT. Test and demonstration of proposed systems is a near term action and specific data will be forthcoming in the near future.

c. Even though there are two systems from which operational data is available, neither of these systems use the latest RF communications technology which may offer significant advantages. The basis for any recommendation requires data on all technologies.

d. There are unknowns related to the application of a railroad oriented control system design to a people-mover system. These unknowns can only be evaluated when system requirements and control system data are available.

e. It is not too early for M-PRT to begin the Systems Engineering that would derive up-front requirements for new technology. The requirements for headway, safety, reliability, maintainability, and interfaces, could be established and available for future application.

APPENDIX A
ACRONYMS

AGRT	Advanced Group Rapid Transit
AGT	Automated Guideway Transit
BART	Bay Area Rapid Transit
CAP	Central Applications Program
CAS	collision avoidance system
C&CS	control and communications system
DAU	data acquisition unit
DEC	Digital Equipment Corporation
DHU	data handling unit
DOT	Department of Transportation
DSU	destination select unit
ESR	executive service request
GCCS	guideway control and communications system
GRS	General Railway Signal
HP	Hewlett Packard
IC	integrated circuit
IEC	International Electrotechnical Commission
I/O	input/output
ISO	International Organization for Standardization
LAN	local area network
M-PRT	Morgantown Personal Rapid Transit
MSAP	Maintenance Station Applications Program
MTA	Metropolitan Transit Authority
MTBF	mean time between failures
ODDCAS	Odometer Data Downlink Collision Avoidance System
O&M	operations and maintenance
OS	operating system
PBD	passenger boarding display
PC	personal computer
PD	presence detector
PDL	program design language
PRT	personal rapid transit
PSAP	Passenger Station Applications Program
RF	radio frequency
ROM	rough-order of magnitude
RTOS	real-time operating system
SCCS	station control and communications system
SIL	system integration laboratory
SPE	Special Purpose Equipment
TTC	Toronto Transit Commission
UHF	ultra-high frequency
VCCS	vehicle control and communications system
VHF	very-high frequency
WVU	West Virginia University

APPENDIX B
REFERENCES

1. MPRT-1-1, *Morgantown Personal Rapid Transit System Operation Description Manual.*

2. UMTA-MA-06-0048-80-8, Rucker, Jim I. and Bert J. Hill, *Morgantown People Mover Redundant Computing System Design Summary*, Boeing Aerospace Company, September 1980.

3. UMTA-WA-06-0011-86-1, Don D. Lyttle, Dave B. Freitag, Doug H. Christenson, *Advanced Group Rapid Transit, Phase IIB, Executive Summary and Final Report,* Boeing Aerospace Company, March 1986.

4. IEEE Std 1003.1b-1993, *IEEE Standard for Information Technology--Portable Operating System Interface (POSIX)--Part 1: System Application Program Interface (API)- Amendment 1: Realtime Extension [C Language],* April, 1994

5. ISO/IEC 8652:1995, *Information Technology --Programming Languages--Ada*

6. D191-94003-1, Interface Control Document for the Control & Communications System of the Phase II Extension of the Morgantown Personal Rapid Transit System

7. D191-94501-1 Revision A, MPRT Phase II - Operational Software Subsystem Design Description - Overview, November 2, 1977.

8. D191-94502-3, MPRT Phase II - Users' Guide - Executive Program, December 7, 1977.

9. D191-94517-2, Computer Program Product Specification for Station Applications Program

10. D191-94591-1 Revision A, MPRT Phase II - Simulation Software Design Description - Overview, December 20, 1977.

11. Boehm, Barry W., *Software Engineering Economics*, Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 1981.

12. De Leuw, Cather & Company study: *New Technology Signal System Study*; done for MTA, New York City Transit, dated October 5, 1994.

13. Gibson, Chuck, "FLEXIBLOK™ Answering the Need for Safe and Economical Automatic Train Control," AEG Transportation Systems, Inc., 1995.

14. Hoelscher, Jim, General Railway Signal Corp., and Fayos, John, Sensis Corp., "ATLAS™ The Next Generation Train Control System," presented at the 1995 Amercian Public Transit association Rapid Transit conference, New York, NY, June 12, 1995.

15. Nishinaga, Eugene, and Evans, John A., Bay Area Rapid Transit District, Mayhew, Gregory L., Hughes Aircraft Company, "Wireless Advanced Automatic Train Control," *Proceedings of the 1994 ASME/IEEE Joint Railroad Conference*, May 1994.

16. Quarterman, J. S.,*UNIX, POSIX, and Open Systems: the Open Standards Puzzle,* Addison-Wesley, Redding, MA, 1993.

17. Riehle, Richard, "An Ada for the Rest of Us," *Embedded Systems Programming*, November, 1995.

18. Tanenbaum, Andrew S., *Modern Operating Systems,* Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 1992.

19. Van Tyle, Sherrie, "A Designer's Guide to Real-Time Operating Systems," *Electronic Design*, Volume 43, No. 17, August 21, 1995.

20. Schleider, Peter, "The Embedded System Opportunity," Wessels, Arnold & Henderson Industry Report, February 16, 1995.

21. Union Switch & Signal, "US&S MICROBLOK™ SYSTEM New Technology building on Proven Signaling & Train Control."

22. "Boeing Revisits Morgantown," *Transit Pulse*, Vol. XIII, No. 5, January/February 1996.

23. "International Conferences on Communications-Based Train Control," *Proceedings*, Crystal City Marriott, Arlington, VA, May 9-10, 1995. Sponsored by Railway Age, in association with De Leuw, Cather.

24. "Maggaly,"MATRA Transport, brochure.

25. "Merger of Rail Activities between ABB and AEG Daimler-Benz Industrie," *Daimler-Benz News*, March 16, 1995.

26. "New York: All signals are 'go'," *Railway Age*, June 1994, pp. 41-49.

27. *pSOSystem System Concepts,* Integrated Systems, May, 1995.

28. *Precise Real-Time Executive,* Intermetrics Microsystems Software, 1994.

29. "SELTRAC® Keeping the Future on Track," Alcatel Canada, SEL Division, brochure.

30. "TTC prepares to switch," *Railway Age*, September 1995, pp. 79-84.

31. *VxWorks Reference Manual 5.3*, Wind River Systems, November, 1995.

32. "Where we are, where we're going," *Railway Age*, July 1995, pp. 41-47.

APPENDIX C
SOFTWARE COST ESTIMATES

COCOMO outputs will be put here.

Equivalent Source Lines of Code (ESLOC)

		Reused KSLOC =	9.0
New (K) =	0.5	Percent Redesign =	25
Reuse (K) =	6.3	Percent Recode =	100
KESLOC =	**6.8**	Percent Retest =	100

	Process Model Scaling Weights	
W1 =	0.03	Experience with Process
W2 =	0.01	Design Thoroughness
W3 =	0.01	Risk Reduction
W4 =	0.00	Requirements Volatility
Sigma =	**0.05**	

Effort Driver	**Effort Multiplier**
RELY =	1.40 VH
DATA =	1.00 NOM
CPLX =	1.00 NOM
RUSE =	1.00 NOM
ACAP =	1.00 NOM
PCAP =	1.00 NOM
AEXP =	1.13 LOW
VEXP =	1.10 LOW
LEXP =	1.00 NOM
TIME =	1.00 NOM
STOR =	1.00 NOM
VMVH =	0.92 L
VMVT =	0.93 L
TURN =	0.79 VL
MODP =	1.00 NOM
TOOL =	0.73 EH
SCED =	1.00 NOM
SECU =	1.00 NOM
Effort Adjustment Factor (EAF) =	0.86

Effort estimates include supervisors, designers, coders,
testers, configuration engineers, and QA.

The schedule estimate begins at completion of the S/W
Specification Review (SSR) and ends at completion of
Formal Qualification Testing (FQT).

Reuse = Reused*(.4*Redesign+.3*Recode+.3*Retest)/100
EAF = The Product of the Effort Multipliers
Labor-Months = 2.8*EBIZ*EAF*KESLOC**(1.04+Sigma)
Schedule(mo.) = 3* SBIZ *LM**(.32+.2*Sigma)

EBIZ = 1.00

SBIZ = 1.00

Note: EBIZ and SBIZ coefficients adapt COCOMO to your business environment.

COCOMO Estimates	Preliminary Design	Detailed Design	Code and Unit Test	Integration and Test	SSR thru FQT Totals
Labor-Months	4.5	5.6	4.3	5.1	19.4
Labor-Hours	679	856	650	768	2953
Schedule Mo.	3.1	2.0	1.2	1.7	8.0
			Productivity (SSR thru FQT) =	**350**	**ESLOC/LM**

Figure C-1. COCOMO Output for Central Applications Program

Equivalent Source Lines of Code (ESLOC)

		Reused KSLOC =	4.5
New (K) =	0.1	Percent Redesign =	20
Reuse (K) =	3.1	Percent Recode =	100
KESLOC =	**3.2**	Percent Retest =	100

	Process Model Scaling Weights	
W1 =	0.03	Experience with Process
W2 =	0.01	Design Thoroughness
W3 =	0.01	Risk Reduction
W4 =	0.00	Requirements Volatility
Sigma =	**0.05**	

Effort Driver	**Effort Multiplier**
RELY =	1.40 VH
DATA =	1.00 NOM
CPLX =	1.00 NOM
RUSE =	1.00 NOM
ACAP =	1.00 NOM
PCAP =	1.00 NOM
AEXP =	1.13 LOW
VEXP =	1.10 LOW
LEXP =	1.00 NOM
TIME =	1.00 NOM
STOR =	1.00 NOM
VMVH =	0.92 L
VMVT =	0.93 L
TURN =	0.79 VL
MODP =	1.00 NOM
TOOL =	0.73 EH
SCED =	1.00 NOM
SECU =	1.00 NOM
Effort Adjustment Factor (EAF) =	0.86

Effort estimates include supervisors, designers, coders,
testers, configuration engineers, and QA.

The schedule estimate begins at completion of the S/W
Specification Review (SSR) and ends at completion of
Formal Qualification Testing (FQT).

Reuse = Reused*(.4*Redesign+.3*Recode+.3*Retest)/100
EAF = The Product of the Effort Multipliers
Labor-Months = 2.8*EBIZ*EAF*KESLOC**(1.04+Sigma)
Schedule(mo.) = 3* SBIZ *LM**(.32+.2*Sigma)

EBIZ = 1.00

SBIZ = 1.00

Note: EBIZ and SBIZ coefficients adapt COCOMO to your business environment.

COCOMO Estimates	Preliminary Design	Detailed Design	Code and Unit Test	Integration and Test	SSR thru FQT Totals
Labor-Months	1.9	2.4	1.9	2.2	8.4
Labor-Hours	295	371	282	333	1281
Schedule Mo.	2.4	1.5	0.9	1.3	6.1

Productivity (SSR thru FQT) = **375 ESLOC/LM**

Figure C-2. COCOMO Output for Passenger Station Application Program

Equivalent Source Lines of Code (ESLOC)

		Reused KSLOC =	0.7
New (K) =	0.0	Percent Redesign =	10
Reuse (K) =	0.4	Percent Recode =	100
KESLOC =	**0.4**	Percent Retest =	100

	Process Model Scaling Weights		**Effort Driver**	**Effort Multiplier**
			RELY =	1.40 VH
W1 =	0.03	Experience with Process	DATA =	1.00 NOM
W2 =	0.01	Design Thoroughness	CPLX =	1.00 NOM
W3 =	0.01	Risk Reduction	RUSE =	1.00 NOM
W4 =	0.00	Requirements Volatility	ACAP =	1.00 NOM
Sigma =	**0.05**		PCAP =	1.00 NOM
			AEXP =	1.13 LOW
			VEXP =	1.10 LOW
			LEXP =	1.00 NOM
			TIME =	1.00 NOM
			STOR =	1.00 NOM
			VMVH =	0.92 L
			VMVT =	0.93 L
			TURN =	0.79 VL
			MODP =	1.00 NOM
			TOOL =	0.73 EH
			SCED =	1.00 NOM
			SECU =	1.00 NOM
			Effort Adjustment Factor (EAF) =	0.86

Effort estimates include supervisors, designers, coders,
testers, configuration engineers, and QA.

The schedule estimate begins at completion of the S/W
Specification Review (SSR) and ends at completion of
Formal Qualification Testing (FQT).

Reuse = Reused*(.4*Redesign+.3*Recode+.3*Retest)/100
EAF = The Product of the Effort Multipliers
Labor-Months = 2.8*EBIZ*EAF*KESLOC**(1.04+Sigma)
Schedule(mo.) = 3* SBIZ *LM**(.32+.2*Sigma)

EBIZ = 1.00

SBIZ = 1.00

Note: EBIZ and SBIZ coefficients adapt COCOMO to your business environment.

COCOMO Estimates	Preliminary Design	Detailed Design	Code and Unit Test	Integration and Test	SSR thru FQT Totals
Labor-Months	0.2	0.3	0.2	0.2	0.9
Labor-Hours	32	41	31	37	140
Schedule Mo.	1.1	0.7	0.4	0.6	2.9

Productivity (SSR thru FQT) = 450 ESLOC/LM

Figure C-3. COCOMO Output for Maintenance Station Application Program

Equivalent Source Lines of Code (ESLOC)

			Reused KSLOC =	0.5
New (K) =	0.5		Percent Redesign =	25
Reuse (K) =	0.4		Percent Recode =	100
KESLOC =	**0.9**		Percent Retest =	100

	Process Model Scaling Weights		**Effort Driver**	**Effort Multiplier**
			RELY =	1.40 VH
W1 =	0.03	Experience with Process	DATA =	1.00 NOM
W2 =	0.01	Design Thoroughness	CPLX =	1.00 NOM
W3 =	0.01	Risk Reduction	RUSE =	1.00 NOM
W4 =	0.00	Requirements Volatility	ACAP =	1.00 NOM
Sigma =	**0.05**		PCAP =	1.00 NOM
			AEXP =	1.13 LOW
			VEXP =	1.10 LOW
			LEXP =	1.00 NOM
			TIME =	1.00 NOM
			STOR =	1.00 NOM
			VMVH =	0.92 L
			VMVT =	0.93 L
			TURN =	0.79 VL
			MODP =	1.00 NOM
			TOOL =	0.73 EH
			SCED =	1.00 NOM
			SECU =	1.00 NOM
			Effort Adjustment Factor (EAF) =	0.86

Effort estimates include supervisors, designers, coders,
testers, configuration engineers, and QA.

The schedule estimate begins at completion of the S/W
Specification Review (SSR) and ends at completion of
Formal Qualification Testing (FQT).

Reuse = Reused*(.4*Redesign+.3*Recode+.3*Retest)/100
EAF = The Product of the Effort Multipliers
Labor-Months = 2.8*EBIZ*EAF*KESLOC**(1.04+Sigma)
Schedule(mo.) = 3* SBIZ *LM**(.32+.2*Sigma)

EBIZ = 1.00

SBIZ = 1.00

Note: EBIZ and SBIZ coefficients adapt COCOMO to your business environment.

COCOMO Estimates	Preliminary Design	Detailed Design	Code and Unit Test	Integration and Test	SSR thru FQT Totals
Labor-Months	0.5	0.6	0.4	0.5	2.0
Labor-Hours	70	89	67	80	306
Schedule Mo.	1.5	0.9	0.6	0.8	3.8

Productivity (SSR thru FQT) = **422 ESLOC/LM**

Figure C-4. COCOMO Output for Executive Program

Equivalent Source Lines of Code (ESLOC)

		Reused KSLOC =	5.0
New (K) =	0.0	Percent Redesign =	25
Reuse (K) =	3.5	Percent Recode =	100
KESLOC =	**3.5**	Percent Retest =	100

	Process Model Scaling Weights		**Effort Driver**	**Effort Multiplier**
			RELY =	1.00 NOM
W1 =	0.03	Experience with Process	DATA =	1.00 NOM
W2 =	0.01	Design Thoroughness	CPLX =	1.00 NOM
W3 =	0.01	Risk Reduction	RUSE =	1.00 NOM
W4 =	0.00	Requirements Volatility	ACAP =	1.00 NOM
Sigma =	**0.05**		PCAP =	1.00 NOM
			AEXP =	1.13 LOW
			VEXP =	1.10 LOW
			LEXP =	1.00 NOM
			TIME =	1.00 NOM
			STOR =	1.00 NOM
			VMVH =	0.92 L
			VMVT =	0.93 L
			TURN =	0.79 VL
			MODP =	1.00 NOM
			TOOL =	0.73 EH
			SCED =	1.00 NOM
			SECU =	1.00 NOM
			Effort Adjustment Factor (EAF) =	0.61

Effort estimates include supervisors, designers, coders,
testers, configuration engineers, and QA.

The schedule estimate begins at completion of the S/W
Specification Review (SSR) and ends at completion of
Formal Qualification Testing (FQT).

Reuse = Reused*(.4*Redesign+.3*Recode+.3*Retest)/100
EAF = The Product of the Effort Multipliers
Labor-Months = 2.8*EBIZ*EAF*KESLOC**(1.04+Sigma)
Schedule(mo.) = 3* SBIZ *LM**(.32+.2*Sigma)

EBIZ = 1.00

SBIZ = 1.00

Note: EBIZ and SBIZ coefficients adapt COCOMO to your business environment.

COCOMO Estimates	Preliminary Design	Detailed Design	Code and Unit Test	Integration and Test	SSR thru FQT Totals
Labor-Months	1.5	2.0	1.5	1.7	6.7
Labor-Hours	235	297	225	266	1023
Schedule Mo.	2.2	1.4	0.8	1.2	5.6

Productivity (SSR thru FQT) = **520 ESLOC/LM**

Figure C-5. COCOMO Output for Environmental Simulator Program

APPENDIX D
DRAFT STATEMENT OF WORK FOR THE M-PRT COMPUTER UPGRADE PROGRAM

1.0 Scope

The purpose of this effort is to implement the recommendations developed under West Virginia University Research Corporation Purchase Order #40577 for upgrading the Morgantown Personal Rapid Transit (M-PRT) system computers and rehosting the existing operational software. The objective is to continue operations at the existing or better service levels through at least the year 2010.

2.0 Applicable Documents

D191- 94003-1	Interface Control Document for the Control & Communications System of the Phase II Extension of the Morgantown Personal Rapid Transit System
D191-94501-1	Operational Software Subsystem Design Description
D191-94501-1	CPDS for Executive Program
D191-94502-2	CPPS for Executive Program
D191-94508-1	CPDS for Central Applications Program
D191-94508-2	CPPS for Central Applications Program
D191-94510-1	Test Description - Central Applications Program
D191-94511-1	Test Procedure - Central Applications Program
D191-94517-1	CPDS for Station Applications Program
D191-94517-2	CPPS for Station Applications Program
D191-94519-1	Computer Program Test Description - Station Software
D191-94520-1	Test Procedures - PSAP
D191-94526-1	CPDS for Maintenance Application Program
D191-94526-2	CPPS for Maintenance Application Program
D191-94555-1	Computer Program Test Description - MPRT Software Subsystem
D191-94558-1	Structure and Content of the Data Bases - Operational Software
D191-94559-1	ICD - Operational Software
S191-94500-1B	Software Requirements Specification for the Phase II MPRT Operational Software Subsystem
WVUBOR-TD-001	Performance/Design and Qualification for the Phase II Morgantown Operational Personal Rapid Transit System, General Specification for
191-84301	Medical Center Station Electronics Assembly
191-84302	Towers Station Electronics Assembly
191-84303	Engineering station Electronics Assembly
191-84304	Maintenance Station Electronics Assembly
2371150	Walnut Sta. SCCS Installation
2371250	Beechurst Sta. SCCS Installation
191-84810	Central Control Computer Configuration

191-84820	Walnut Computer Configuration
191-84830	Beechurst Computer Configuration
191-84840	Maintenance Computer Configuration
191-84850	Engineering Station Computer Configuration
191-84860	Towers Computer Configuration
191-84870	Medical Center Computer Configuration

3.0 Requirements

2.1 Computer Platform Upgrade

2.1.1 Architecture Definition. The contractor shall develop a computer system architecture that uses Intel X86 computer platforms to replace the existing Digital Equipment Corporation (DEC) PDP 11 computers and the special purpose equipment that interfaces the computers with other electronics at the stations and central.

2.1.2 Reliability and Availability Analysis. The contractor shall perform an analysis to verify that the new computer system mean-time-between-failures exceeds 200 hours, the best performance experienced by present system through 1995. The contractor shall identify the quantity of spare parts required to maintain or exceed the highest level of computer system availability achieved through 1995. Contractor shall provide analysis and provisioning data to WVU.

2.1.3 Safety and Operability Analysis. The contractor shall perform an analysis to verify that the computer system upgrade does not negatively impact safety and operability. Contractor shall provide analysis data to WVU.

2.1.4 Drawings and Data. The contractor shall prepare interface drawings for each unique configuration. The contractor shall prepare procurement specifications for the processors and interface equipment. The contractor shall prepare procurement specifications or drawings for station electronics/computer interface cables. The contractor shall prepare installation drawings for the computer hardware at each station and central. Contractor drawing format shall be consistent with present installation drawings. WVU will provide present system drawing data as required by contractor. "As Built" drawings will be delivered to WVU after completion of installation.

2.1.5 Procurement. The contractor shall procure all equipment and spares required for the computer system upgrade.

2.2 Operational Software Rehost

2.2.1 Operating System Selection. The contractor shall review the three operating systems recommended in the upgrade study. The contractor shall select one of the operating systems for procurement based on the available features, tools, contractor experience with the operating system, and life cycle cost. The contractor shall procure the operating system, development environment, and support licenses necessary to support development and complete testing of the upgraded system.

2.2.2 Design Review and Update. The contractor shall review and the existing design documentation and update it to reflect changes to the computing system configuration, including operating system. The contractor shall design changes required to incorporate circulation mode and programmable boarding displays into the applications software.

2.2.3 Implementation. The contractor shall translate the existing code into ANSI C high order language and implement design changes. The contractor shall update the test descriptions and test procedures for consistency with the computing architecture and software design changes. The contractor shall perform unit testing of the rehosted software.

2.2.4 Integration and Test. The contractor shall develop any tools required to integrate and test the rehosted software. At a minimum, these tools will include a real-time simulation. The contractor shall integrate and test the rehosted software. The contractor shall perform comprehensive testing of the upgraded system at the contractor facility prior to installation at WVU.

2.2.5 Documentation. The contractor shall update and prepare electronic versions of the following M-PRT documents: Software Requirements Specification, Operational Software Design Description, the Computer Program Development Specifications (Part 1's,) Operational Software ICD, the Structure and Content of the Data Bases, computer program test descriptions, and computer program test procedures. The contractor shall revise pages of the Computer Program Product Specifications as required.

2.3 System Test Planning

The contractor shall develop system test plans and procedures and coordinate them with WVU personnel. The contractor shall conduct a Test Readiness Review on completion of integration and test at the contractor facility.

2.4 Installation and Test

2.4.1 Hardware Installation and Checkout. WVU will provide the contractor access to the areas where equipment is to be removed and/or installed. The contractor shall coordinate the installation schedule with WVU for approval. The contractor shall direct the activities of technicians to be provided by WVU to remove and dispose of the existing PDP11 computers and displays, special purpose equipment and associated cabling. The contractor shall direct the activities of technicians to be provided by WVU in the installation and checkout of the new computers and associated cabling. This installation and checkout will include power on, diagnostics, and inter-computer communications checkout to assure that the installation is ready to proceed with system test. WVU will obtain all permits necessary to support installation activities.

2.4.2 Software Checkout. The contractor shall load the rehosted software and verify basic functionality. WVU technicians will provide support this activity.

2.4.3 System Test. The contractor shall direct M-PRT operators in the conduct of system tests to confirm operational integrity prior to passenger carrying operations. The contractor shall resolve and correct any problems with the computer system hardware or software that may be discovered during this testing.

2.5 Commercial Manuals

The contractor shall determine commercial operations and maintenance manual requirements and coordinate them with WVU. The contractor shall procure the manuals and deliver them to WVU.