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ASSESSMENT OF WASHINGTON METROPOLITAN AREA RAIL RAPID TRANSIT SYSTEM

U.S. Department of Transportation
Research and Special Programs Administration
Transportation Systems Center
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PROJECT MEMORANDUM

Prepared for

U.S. DEPARTMENT OF TRANSPORTATION
URBAN MASS TRANSPORTATION ADMINISTRATION
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PREFACE

This report is the result of an assessment of the WMATA Metrorail System which took place over a six-month period between April and October of 1978. The report not only provides a general description and status of the system at that time, but also focuses on those current problem areas having a significant impact on the service and operation of the system. In addition, specific recommendations by the assessment team for supporting the resolution of each key problem area are included, along with lessons learned from WMATA's experience to date that could be useful to other transit properties. <u>It should be recognized that the information and recommendations in this report were consistent with the status of the Metrorail System at the time of the assessment in mid-1978; since that time, expansion of the system plus on-going problem resolution efforts by WMATA have changed the currentness of some of the report content</u>.

Overall responsibility for the assessment project was under the general direction of UMTA's Office of Technology Development and Deployment, Office of Safety and Product Qualification. Management and conduct of the assessment was provided personally by members of the technical staff of the U.S. Department of Transportation's Transportation Systems Center, with support from Alexander Kusko, Inc. and the Lawrence Berkeley Laboratory of the University of California.

The technical areas of focus were selected by the review team during the review process. Responsible for the assessment and preparation of this report in the five areas of interest are the following:

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1. INTRODUCTION

A plan developed in the sixties for providing a regional rapid rail transit system for the Washington, DC Area became a reality on March 29, 1976, with the opening of the Metrorail system on a 4.6-mile section of the Red Line in the Washington, DC area. WMATA is the second automated, high-speed, large-scale rapid transit system to be installed in this country, the first being the Bay Area Rapid Transit (BART) system in San Francisco. The opening of WMATA heralded the start of a new era of transportation for the Washington, DC Area and neighboring counties in Maryland and Virginia. Yet, as has come to be expected with the start-up of any new transportation system, like BART, the Metrorail system had problems during its initial period of operation. With the opening of the Blue Line over a year later in July 1977, Metro's rail mileage tripled and its problems, particularly with the vehicle subsystem and the introduction of automatic fare collection equipment, reached a disturbing level. The resulting service disruptions created a wave of public criticism and controversy, which made it difficult to separate fact from emotional reaction.

It was during this climate of public criticism that the idea of conducting a technical assessment of the Metrorail system developed. Discussions between the Urban Mass Transportation Administration (UMTA) and the Washington Metropolitan Area Transit Authority (WMATA) led to an agreement to have a group of independent, knowledgeable, technical personnel, who could be completely objective, conduct the assessment and establish a general picture of the health of the Metrorail system and the current problems of the system. Additionally, the experience gained from new systems such as Metrorail could provide valuable insight to the rail transit industry, especially for newly emerging properties.

This report is the result of such an assessment, which took place over a six month period between April and October of 1978. The report not only provides a general description and status of the system at that time, but also focuses on those current problem areas having a significant impact on the service and operation of the system. In addition, specific recommendations by the assessment team for supporting the resolution of each key problem area are included, along with lessons learned from WMATA's experience to date that could be useful to other transit properties.

Overall responsibility for the assessment project was under the general direction of UMTA's Office of Technology Development and Deployment, Office of Safety and Product Qualification. Management and conduct of the assessment was provided personally by members of the technical staff at the U.S. Department of Transportation's Transportation Systems Center, with support from Alexander Kusko, Inc. and the Lawrence Berkeley Laboratory of the University of California. The technical areas of focus were selected by the review team during the review process. Responsibility for the assessment and preparation of this report in the five areas of interest is as follows:

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In performing the assessment, the review team relied primarily on discussions with WMATA's management and technical staff, on system documentation (such as operation and maintenance manuals, specifications, and drawings), and on personal observation of the system in operation. After an initial 3-day meeting with the WMATA staff to become familiar with the system and its operation, the review team held several one-on-one discussions with their technical counterparts in the engineering and operations parts of the WMATA organization. These discussions, along with the review team's own observations, analyses, and technical judgement, led to the preparation of an interim report which characterized the general status of the system and identified 21 top priority problems as having the most impact on the Metrorail system in terms of the service it provides (dependability level), the cost of operating and maintaining the system, and the passenger's perception of the system. Over 75 problem areas were identified and characterized in the report as to impact on system, probable causes, and status of resolution. After a review of the interim report by WMATA and a formal briefing to their staff, the review team continued its evaluation in those problem areas mutually acceptable to WMATA. The emphasis of this stage of the assessment was to support WMATA's plan of attack in resolving these problems with some independent analysis and test by the review team. The recommendations in this report are the results of these efforts.

2. SUMMARY OF RECOMMENDATIONS AND CONCLUSIONS

Though the emphasis of the review team during this assessment focused on technical problems currently being experienced by the Metrorail system, an additional outcome of the review was the judgement, on behalf of the team, that the general health of the Metrorail system is currently good and improving. As discussed in more detail in the following chapter, the overall system dependability being achieved by the Metrorail system at the time of this study is at least comparable to other rail rapid transit systems in the United States. In addition, actual system ridership is higher than anticipated and continues to increase. Many problems that existed during the earlier days of revenue operation have been resolved; significant technical problems that currently exist on the system are, in general, recognized by WMATA, and a plan of action has been developed to resolve each problem. Until a solution is available, the impact of any of these problems is minimized by the fact that the system is only partially complete and not operating at full capacity, and also that additional maintenance effort is being provided to accommodate the problem. Current operation at higher-than-design headways, availability of spare trains, and only partial use of the automatic train control functions are some reasons that make the current system operation less sensitive to the technical problems that exist. Upon expansion of the system, however, current problems as discussed in the following chapters, unless resolved, will have a much greater impact on both the service and cost of operation.

A list of recommendations and lessons learned for other transit properties is included at the conclusion of each problem discussion in the following chapters of the report. The intent of this summary is to paraphrase each of the recommendations in the simplest form possible <u>in the same order that they appear in the text.</u> The reader should appreciate that the simple form of each recommendation may more easily be misinterpreted because of its brevity. He should, therefore, refer to the body of the text for fuller understanding. The page number for the corresponding text has been referenced after each recommendation.

System Operations

1) Recommendation - WMATA should methodically reexamine the following operational constraints, based on operational experience to date, to minimize potential degradation in current service that may arise when system is expanded further: overall track plan, available fleet size, tracking and control of schedule times (pg. 3-5).

   Lesson Learned - Opening of a new line section of a system should be preceded by sufficient training of operators and maintenance personnel, by dry-running of new schedules without passengers, and by sequential introduction of major changes such as automatic fare collection equipment and short turning of feeder buses (pg. 3-6).

2) Recommendation - WMATA should automate their management information system to facilitate more extensive analysis conducive to improving service and reducing maintenance costs (pg. 3-12).

   Lesson Learned - An automated management information system should be designed, developed, and in place before the first new vehicles arrive on the property and should be used continuously thereafter (pg. 3-12).

3) Recommendation - WMATA should consider changing their definition of system availability/dependability to the more stringent definition used by PATCO and NYCTA. Also, WMATA should participate in an on-going effort with other properties to converge on common definitions for reporting system performance measures (pg. 4-3).

Lesson Learned - The measures used for defining system availability/dependability should reflect the following factors:

- A predictable value that is linked to overall system design and that can be verified through revenue testing.
- Management's desired transportation service objective.
- Use as a frequent indicator of the rate at which transportation service is changing due to new section openings or other similar major events (pg. 4-8).

4) Recommendation - WMATA initiate a more vigorous, organizationally-coordinated attack on their high priority problems via the recommended approaches. Also that diagnostic and failure-indication capability on-board the vehicle be reexamined, based on operating experience to date (pgs. 4-12 and 4-13).

Lesson Learned - Design of the vehicles' "system effectiveness attributes" (cut-out capabilities, diagnostics, etc.) is extremely important to achievement of high levels of system dependability (pg. 4-14).

Vehicle Subsystem

1) Recommendation - WMATA initiate a test program involving measurement of the vertical and lateral forces generated by the interaction between the wheels and the rail. These measurements will be used to evaluate proposed configuration changes to the vehicle and/or the track as well as operational changes which are all being considered as a means to reduce the wear rate of the wheels and the rails (pg. 5-13).

Lessons Learned - Known and accepted practices that are utilized by the transit industry to reduce wheel and rail wear (i.e., guard rails, lubricators, etc.) should be seriously considered in the overall design of a transit system (pg. 5-14).

Dynamic analysis of the truck design and dynamic testing of the first vehicle truck should be included in vehicle specifications to determine the dynamic response of the truck and its effect on the vehicle and the track (pg. 5-14).

When developing specifications for a transit system, attention should be given to conducting trade-off analyses between safety, ride comfort and performance, and the cost involved in achieving and maintaining adequate levels of these criteria (pg. 5-14).

2) <u>Recommendation</u> - Beyond continuing the test and evaluation of alternative brake pad materials, WMATA should review and evaluate the proposal by Westinghouse Electric to utilize dynamic braking in the B-1 brake mode (pg. 5-16).

<u>Lesson Learned</u> - Thorough trade-off studies should be conducted early in the design phase to understand advantages/disadvantages of design alternatives (i.e., WMATA's choice of braking concept for better response time is contributor to penalty of excessive friction brake wear) (pg. 5-17).

Specification for the vehicle should include requirements for normal life cycle wear of the braking system in addition to the emergency life cycle wear (pg. 5-16).

3) <u>Recommendation</u> - WMATA should consider requesting Safety Electric to redesign the ATC power supply and to incorporate design features that have been lacking previously. Also, WMATA should include these design features as ATC power supply requirements in the newest vehicle-buy specification (pg. 5-18).

Lesson Learned - Design and test requirements for an ATC power supply should be included in the train control specification and should be the responsibility of the train control supplier, as opposed to the vehicle specification and the car supplier, respectively (pg. 5-18).

4) Recommendation - WMATA should consider replacing both the door-motor control relay and the door-limit switch mounting bracket on-board the vehicle (pg. 5-20 and pg. 5-22).

Lesson Learned - Transit properties should define in the vehicle specification a requirement for testing of certain subsystems and components under proper environmental conditions (pgs. 5-21 and 5-22).

5) Recommendation - WMATA should initiate immediately a modification program to address the Carborne Monitor (CBM) interfacing problem (pg. 5-26).

The Carborne Monitor be further evaluated as a test/evaluation and diagnostic/maintenance tool by WMATA through the use of the CBM in problem areas associated with braking, propulsion, and program stopping (pg. 5-30).

Lesson Learned - The Carborne Monitor concept and its utilization during both the development and operational phases of a transit system should be considered by transit properties during initial cost tradeoffs associated with the cost of diagnostic equipment versus the cost of maintenance without diagnostic aids (pg. 5-30).

6) Recommendation - WMATA investigate the use of a simpler design for the brake control valve (pg. 5-31).

Lesson Learned - The more complex a system is, the tighter the requirements should be for quality control procedures and environmental testing in the specification (pg. 5-31).

ATC Subsystem

1) Recommendation - WMATA should examine the capabilities and readiness of the Central Train Control Computer System, particularly with respect to its ability to handle the fully-expanded Metrorail System (pg. 6-23).

   Lesson Learned - New properties, during the conceptual design stage, should seriously consider use of the Metrorail System's provision for manual backup in the event of ATC hardware failures (pg. 6-24).

2) Recommendation - WMATA consider increasing the level of effort presently assigned to the ATC section in Equipment Design, particularly the manpower being assigned to monitor and analyze ATC subsystem reliability data (pg. 6-24).

   Lesson Learned - New properties in the planning stage should have their own train control staff prior to the conceptual design of the ATC system. The operations and maintenance viewpoint in designing the ATC system can easily be neglected unless the authority has developed its own staff (pg. 6-24).

3) Recommendation - WMATA should continue to develop and use diagnostic tools such as the Carborne Monitor and the SYSLOG files, which represent unique opportunities to measure current system performance, and to support resolution of existing hardware problems (pg. 6-23).

   Lesson Learned - New properties should follow WMATA's example in providing a substantial level of maintenance diagnostic test equipment (pg. 6-24).

Station Subsystem

1) Recommendation - WMATA should develop a comprehensive reliability and maintenance data reporting process for station equipment which includes money-handling hardware and those "soft" failures handled by the kiosk operator (pg. 7-8).

Lesson Learned - Use of commercial money-handling equipment for transit application should be minimized until reliability of such equipment is improved and/or proven in a transit environment (pg. 7-9).

2) Recommendation - The restart controls of the escalators should be more conveniently located so that the station attendant can restart the unit for a vandalism type of stoppage (pg. 7-10).

WMATA should not assume the maintenance responsibility for the escalators until sufficient design improvements and retrofits have been implemented to achieve a mean-time-between-failures (MTBF) consistent with conventional, non-modular escalator designs (pg. 7-10).

Lesson Learned - Alternate means of access/egress to platform areas (such as stairways) should be provided to handle passenger traffic when escalators are non-operative. Also, escalator controls should be more accessible to station attendants (pg. 7-10).

Properties should require the escalator vendor to demonstrate a required MTBF prior to ordering specific design. (pg. 7-10).

Power Distribution Subsystem

1) Recommendation - WMATA should initiate action to clean more effectively the air used to ventilate the underground ac service rooms (pg. 8-4).

Lesson Learned - Properties should make use of outside ambient air to ventilate underground ac service rooms where economically feasible. If tunnel air is used, filter design should be two-stage type (pg. 8-4).

2) Recommendation - WMATA should protect Uninterrupted Power Supply (UPS) hardware from environment by coating the circuit boards in the current units with epoxy and by sealing the cabinets (pg. 8-5).

Lesson Learned - Standardization and modularization of the UPS system will simplify maintenance of the system as well as provide a more flexible operation and a safer maintenance environment (pg. 8-6).

3) Recommendation - WMATA upgrade their Ground Fault Current Interruption capability by adding breakers to those branch circuits where the ground faults have occurred most frequently (pg. 8-7).

Lesson Learned - Utilizing additional ground fault protection in the circuit breakers for each branch circuit will limit the zone that is tripped out, so less equipment is down at the time and the cause of the fault is more easily determined (pg. 8-8).

3. OVERVIEW OF SYSTEM OPERATION

3.1 TECHNICAL DESCRIPTION OF OVERALL SYSTEM

The Washington Metropolitan Area Transit Authority (WMATA) Metrorail system was designed as a 100-mile network of five lines, as depicted in Figure 3-1. The system is being built in sections generally starting in the central business district of Washington, D.C. and reaching out to the surrounding suburban areas.

The first major section was opened for revenue service on March 29, 1976 and consisted of 4.2 revenue miles of track and five stations along the Red Line between Rhode Island Ave. and Farragut North stations. Trains shuttle back and forth on the two track mainline, reversing direction at the terminal stations. Gallery Place, located between Metro Center and Judiciary Square, was opened on December 15, 1976. The line was extended one station beyond Farragut North to Dupont Circle (an additional 0.3 revenue miles) on January 17, 1977. The line is supported by Brentwood Yard (repair shop), located between Union Station and Rhode Island Avenue.

The second major section opened for revenue service on July 1, 1977 and included 12 revenue miles and 18 stations of the Blue Line, from the National Airport to Stadium Armory. One station (Metro Center) is a transfer station between the Red and Blue Lines. This line is also supported by Brentwood Yard with some vehicle storage available beyond the terminal stations.

The first few months after the Blue Line opening proved to be a very eventful period in WMATA's short history. It demanded the availability of more than three times the number of vehicles previously used on the Red Line and rapid hiring and training of significantly more train operators and vehicle maintenance personnel. It marked the introduction of the automatic fare collection equipment used in the system. Many bus routes were changed (to shorten them), and at National Airport the system was flooded with an ever increasing number of new patrons. Service dependability on the Blue

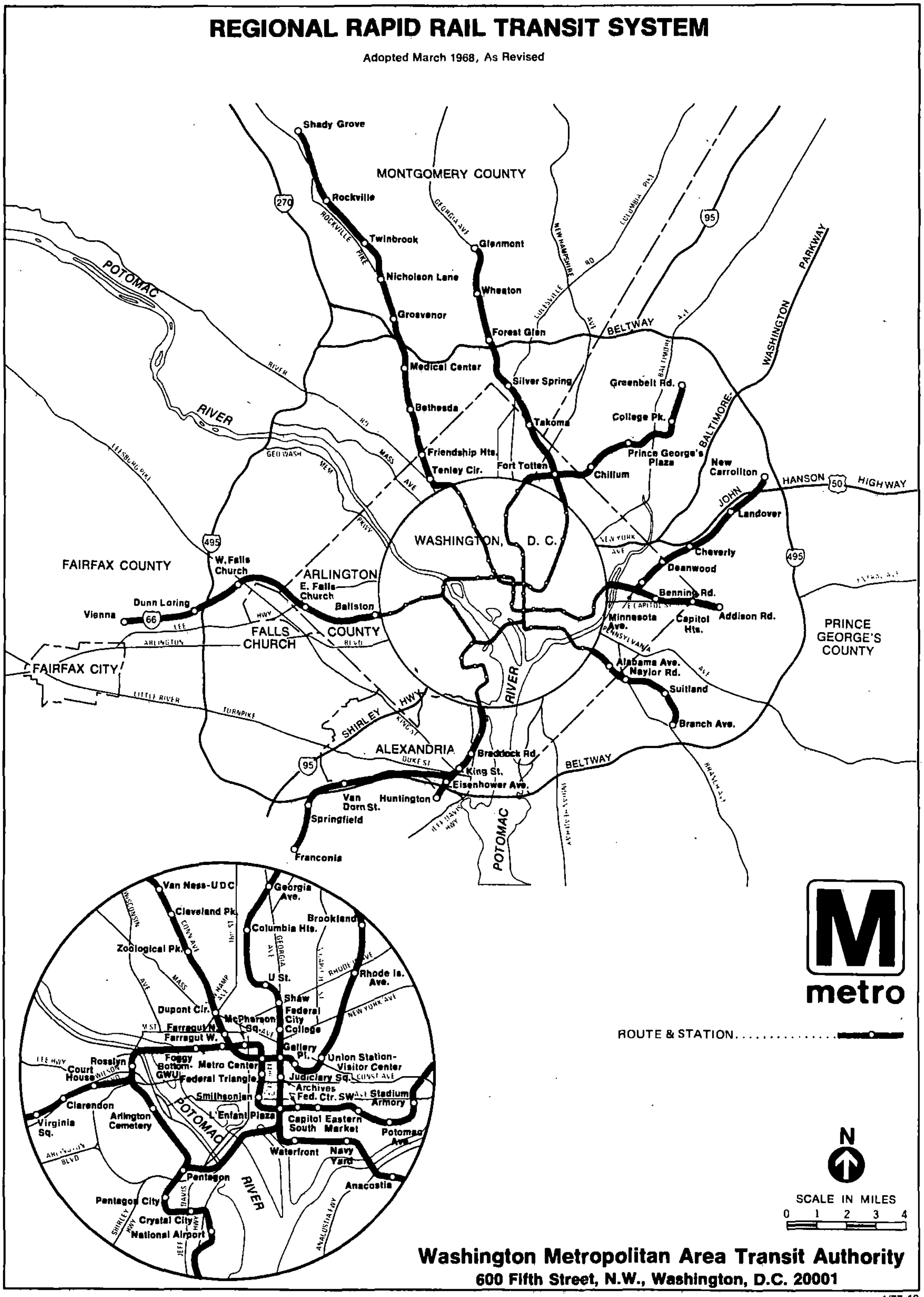


FIGURE 3-1. WMATA REGIONAL RAPID RAIL TRANSIT SYSTEM

Line during its first month of operation was the lowest the overall system has experienced during its history and it also caused a corresponding dip in Red Line service dependability.

The third major section opened for revenue service on February 6, 1978, and consisted of a 5.5-revenue mile extension of the Red Line from Rhode Island Ave. to Silver Spring. It brought the system to a status of 28 stations and 22.0 route miles of revenue track during the time of this study. This extension made the Red and Blue Lines almost equal in length. The opening proved to be relatively uneventful in comparison to the Blue Line opening.

System usage was then about 190,000 passenger trips per day and service was provided five days per week, from 5:00 a.m. to 8:00 p.m. Since September 25, 1978, ridership increased because service hours were expanded; weekday hours became 6:00 a.m. to midnight and Saturday service was added, from 8:00 a.m. to midnight.

The next major opening followed the period of this study and consisted of a 7.5-mile, 5-station extension of the Blue Line out to New Carrollton; operation began during November, 1978.

3.2 DESCRIPTION OF OPERATION

The Blue Line peak period schedule at the time of this study called for thirteen 8-car trains, operating on 6-minute headways, with an 8-car extra train stored at National Airport. The Red Line peak period schedule called for six 6-car trains and six 8-car trains operating on 5-minute headways, with a 6-car extra train stored at Silver Spring (a total of 194 cars), plus a spare train in the Brentwood Yard.

The off-peak period operation required eight 8-car trains on 10-minute headways for the Blue Line and six 6-car trains on 10-minute headways for the Red Line.

Since the track plan was optimized for the intended 100-mile system, operation on smaller sections of this track and at yard and shop locations has been somewhat constrained.

For example, the track arrangement at National Airport, Silver Spring, and especially Stadium Armory, all temporary end-of-the-line terminal stations, were far less than optimum for turnback operations at the time of this study. Brentwood Yard, between Rhode Island Avenue and Union Stations on the Red Line, was designed as a heavy repair facility, and was the only facility available to either the Red or Blue Lines for service and inspection and most unscheduled maintenance functions. The only access from the Blue Line to the Brentwood Yard is via a connector track between the Red and Blue Lines and then along a section of the Red Line. Off peak and overnight vehicle storage was marginally acceptable and created special logistics problems.

Fortunately, these temporary operational constraints have been somewhat offset by the fact that the operational sections were much shorter than the corresponding total line lengths of the planned 100-mile, full-system configuration. The patronage was therefore proportionately lower, allowing longer headways (five and six minutes on the Red and Blue Lines, respectively) in peak periods to be temporarily adequate. These relatively long headways (compared to the 90-second-minimum safe design headway of the automatic train control system) made it possible to move trains through the connector track and dead-head faulty or replacement trains between regularly scheduled trains with relative ease.

Another very important alleviating feature was that the available vehicle fleet, relative to the total order of 300 Rohr vehicles, has almost always been sufficiently large in advance of each section opening to have gap trains in excess of scheduled trains and additional spares in the yard even during peak periods. The short operating day and lack of weekend service (until introduced just before the end of this study) has also helped maintenance personnel to keep the required number of operational vehicles available.

However, now that the last of the new vehicles from the 300 car Rohr order has been received, system operation will be more constrained with each subsequent extension of the system. The worst-case test, before a new car order begins to alleviate the situation again, will probably occur when the Orange Line extension westward from Rosslyn and the Blue Line extension eastward from Stadium Armory create merge points at these two stations and a 3-minute headway trunk line between them. However, the completion of a storage yard beyond New Carrollton should relieve the constraint somewhat.

Recommendations

The major recommendation regarding overall system operation is that WMATA should methodically reexamine the following operational constraints to minimize the potential degradation in current service that may arise when the system is expanded further, and particularly when 3-minute scheduled headways are initiated:

1) The overall track plan of the originally designed 100-mile system, in contrast to current desires based on operational experience to date, with emphasis on temporary terminal turnback configurations; relative size and location of yard, shop, and overnight vehicle storage areas; and temporary storage and movement of disabled and replacement trains during revenue service.

2) The available fleet size and new vehicle availability relative to scheduled train needs, gap train needs, scheduled maintenance requirements, and unscheduled maintenance capability.

3) The ability of individual train operators and central control to track and strategically control schedule times, especially at dispatch and merge points.

Lessons Learned

The major lessons learned from WMATA's experience, both positive and negative, for developing properties to heed are as follows:

1) The opening of a new line section should occur only when there are sufficient spare vehicles,

trained operators, and trained maintenance personnel available well in advance. (WMATA has usually kept ahead in this area.)

2) The opening of a new line section should not occur simultaneously, but sequentially, as much as possible, with correspondingly difficult changes such as the introduction of automatic fare collection equipment and short turning feeder buses.

3) The opening of a new line section should first be tested by operating the full schedule of trains through the new section and stations without passengers for a reasonable test period (Red Line opening, relatively uneventful).

4) The design of the track layout for a large, incrementally-constructed transit system and its defined locations for terminal stations, car storage, and repair facilities should reflect a strong and early operational design input and should be revised, if necessary, as actual experience is gained from operation of initial segments of the system.

3.3 DESCRIPTION OF CURRENT MANAGEMENT INFORMATION SYSTEM

Background

WMATA has kept daily account of the train trips scheduled and train trips completed using a consistent criteria/definition since opening day of the Red Line on March 29, 1976.

This information is computed as follows. Central controllers manually record off-normal incidents on a "Transportation Department-Rail, Summary of Train Operation" log sheet. Separate logs are kept for the two lines currently in operation, the Red Line (A B Route) and the Blue Line (C D Route). A separate "Command Center Supervisor's Report" is also prepared for the more significant line item incidents. The handwritten log sheets for the previous day are typed and widely distributed to all departments. A sample log sheet, for March 17, 1978, is shown in Figure 3-2.

C D ROUTE

TRANSPORTATION DEPARTMENT - RAIL

SUMMARY OF TRAIN OPERATION: DAY FRIDAY DATE MARCH 17, 1978 INITIAL

LTR #	ITEM	CODE	DIR & LINE	LOCATION	TIME	MIN DELAY	TRAIN & TERMINAL	TRIPS ADD	TDL	CAR NUMBER(S) AND DETAILS	PROBLEM CATEGORY
	C160	CMD	SB	All Stations	6:27a	0	STD 5:46a	0	ATC	922-1140 Erratic speed readout	Loss Spd Rdot
	C161	CMD	NB	Pentagon City	6:30a	3	NTL 6:24a	0	ATC	909-1175 Erratic speed readout	Loss Spd Rdot
	C162	CMD		National	6:44a	6/0	NTL 6:44a	2	ATC	904-1185-87 Failed dst.	ATC / Propl
	C163	CMD	SB	Pentagon	6:53a	4	STD 6:26a	0	DRS	901-1223 All doors cut out	Doors
	C164	CMD	NB	Crystal City	7:14a	0	NTL 7:12a	0	SLT	906-1078-1157-Motor overload - power - reset	Mtr Ovld
	C165	CMD	NB	Potomac	7:20a	0	NTL 6:48a	0	DRS	924-1183 Door #11 cut out	Doors
	C166	CMD	SB	All Stations	1:55p	0	NTL 1:50p	0	COM	902-1059 Radio transmitter intermittently	Radio
	C167	CMD	SB	Farragut West	2:21p	0	STD 1:52p	0	WHL	923-1144 Bad flats	Misc
	C168	CMD	NB	C09 to C08	2:36p	10/2	NTL 2:32p	2	ATC	922-1175 ATP cut out, No speed readouts	Loss Spd Rdot
	C169	CMD	NB	Pentagon	3:22p	0	NTL 3:18p	0	SLT	906-1239 Motor overload - power mode- reset	Mtr Ovld
	C170	CMD	SB	Potomac	4:16p	0	STD 4:15p	0	ATC	902-1122 Does not lose program station stop	ATC / Propl
	C171	CMD	NB	All Stations	4:51p	0	NTL 4:50p	0	ATC	909-1243 Not losing program station stops	ATC / Propl
	C172	CMD	SB	All Stations	4:57p	0	STD 4:32p	0	ATC	923-1144 Erratic speed readouts	Loss Spd Rdot
	C173	CMD	SB	Crystal City	5:25p	0	STD 4:56p	0	SLT	904-1137 Motor overload - P mode - reset	Mtr Ovld
	C174	CMD	SB	All Stations	5:33p	5	STD 5:06p	2	ATC	906-1238 Erratic speed readout	Loss Spd Rdot
										TOTAL TRIPS 222 TOTAL CAR MILES 16,663.2	

FIGURE 3-2. SUMMARY OF TRAIN OPERATIONS C D ROUTE (BLUE LINE), MARCH 17, 1978

An "aborted trip" on these log sheets is defined as one which does not complete at least the first three station stops of a scheduled trip. (This definition stems from the original 5-station Red Line system where completion of three station stops was the majority of the trip, but is now inappropriate, since each line is now at least 11 stations long). If an "aborted trip" train cannot be restored to service quickly or a space train is not available to take its place in the next scheduled dispatch, other aborted trips can accumulate from a single incident. A "Train Interval Sheet" is used to record actual times when different from schedule and train consist vehicle numbers. The aborted trips for the day are subtracted from the scheduled trips to deduce the "Total Trips" entry on the form. The train schedule and "Operator Run Cards" typically change only every several months.

Each incident on the "Summary of Train Operation" log sheet is also tagged as one of 18 possible categories of "problems." Each day's problems then appear as one line on a cumulative, month-long "Daily Summary, Rail Operations, Problems" log sheet. A sample of this type of log sheet is shown in Figure 3-3 for the month of March, 1978. The March 17, 1978 problem categories from the Figure 3-2 example have been highlighted on Figure 3-3.

When the central controller participates in the resolution of an incident, he calls the appropriate maintenance trouble desk to report problems. The majority of incidents on the Summary of Train Operations log are vehicle related and each of these initiates the preparation of a "Vehicle Service Report" (VSR). These reports are tagged with the corresponding "Item" number from the Summary of Train Operations log. An example VSR for "Incident 168" of Figure 3-2 is shown in Figure 3-4. VSRs are also initiated from other means such as the daily safety checks, train operator walkthroughs, etc.

The "Vehicle Work Order" (VWO) form is similar in function to the VSR except it is used for scheduled maintenance activity instead of unscheduled maintenance activity covered by the VSR. There are typically about 70 VSRs and a dozen VWOs per week day to contend with.

DAILY SUMMARY

RAIL OPERATIONS

MONTH OF March 1978

C D ROUTE

DATE	PASSENGERS	HANDI-CAPPED	TRIPS	%%%%%%%%%%%%	ATC P. ROP L	ATO STOP USED	BRAKES	BRK LIGHT	BRK SHOES	BRK AIR PRES	COMPUTER	DOORS	ENVIRONMENTAL	LONG/SHORT STOP	LOSS PROP	LOSS SPD RDOT	MISCELLANEOUS	MTR OVERLOAD	RADIO	SIGNAL	STA SKIP	UNDESIRED STOP	TOTAL
1			225	98.6	2					1		5		4		4	2	4					22
2			222	97.3	1		1			4		2		3	1	3	1	3		1			20
3			220	96.4	3			1		1		4		3		2	1	6					21
6			224	98.2	3							2		2		2		1					10
7			220	96.4	4		1	1		3		4		2		2		4	1	1			23
8			221	96.9	1		1			1		2	1	1		1	2			1			11
9			226	99.1	4							1	1	2				3					11
10			223	97.8	2							4				2		2					10
13			223	97.8	1		1	1		1		4				1	1	2					12
14			226	99.1	1							1				2	1						5
15			217	95.1	1							1				1	2	1					6
16			224	98.2	2		1					1			2	2							8
17			222	97.3	3							2				5	1	3	1				15
20			226	99.1	1		2	1				1				1	1	3					10
21			225	98.6				1				1				2	1	1	1				7
22			227	99.5	2			2		1				2	1	2							10
23			228	100.	3			1						2	1		2						10
24			226	99.1	1							2		1		4	1	2	1				12
27			223	97.8	1		1					1		2		3	1	3					12
28			228	100.	2							1	2				3	2					10
29			228	100.	1					1		1					2	3					8
30			222	97.3			1					1	1			3							6
31			227	99.5	1		1					4		1		1		4					12

FIGURE 3-3. DAILY SUMMARY RAIL OPERATIONS C D ROUTE (BLUE LINE), MARCH 1978

117 ... 10/2

KEY	CAR NO. 175	VSR NO. 14863	WORK ORDER NO. 8579	V S R	DATE M M D D Y Y 031778	TIME
HDR	ASG 17	MILES 20164	OPER. HOURS 9887	INCIDENT 168	REL-VSR	VEHICLE SERVICE REPORT

FAILURE

WHEN DISC. 01 | SYM. 193 | CONSQ-SERV C | PRI B

FAILURE REPORT DESCRIPTION: Eratic spd read-outs (2nd up today) from Crystal to Pentagon

RECEIVED OR DISCOVERED BY: SIGNATURE Ogden

LOOK

HOW ID	LOC	FAIL	CRT ACT	SHOP SHIFT CREW	ELAP.	MHRS.	DATE	TIME
15B / 99		44	77	47N	.	.	031778	1640

DESCRIPTION OF CONDITION AND COMPONENTS AS INVESTIGATED: Constant problem, ATP module changed several times & no help. Tranferring to Shop per instruct.

MAR 21 1978

INVESTIGATED BY: SIGNATURE Adams

ACTION

DEFERRED CODE	DATE	TIME	TEST	APRNT. FAIL
	032078	1600	35	910

REMARKS: Checks OK - Loos

CAR RELEASED

FIGURE 3-4. VEHICLE SERVICE REPORT: INCIDENT 168, MARCH 17, 1978 (Sheet 1)

VSR | CAR NO. 1294 | S/A 15B | HDW-ID 1.99 | 19863 | A/S H | MILES 2064 | VEHICLE WORK ORDER 008579 | M

KEY | WHEN DISC 01 | SYM 793 | ESP 441 | S/S-HDW-ID 15B 1 99 | REL-VSR 15412 | DATE 031778 | OPEN TIME 1645

DISCREPANCY DESCRIPTION: Erratic speed readouts from Crystal to Pento

DELAY CODE	ELAP	SHOP SHIFT CREW
CODE	ELAP	SHOP SHIFT CREW
CODE	ELAP	SHOP SHIFT CREW

Freeman
SIGNATURE

M A C T 1

HDW-ID	METRO PART NUMBER	SN-ON	SN-OFF	QTY	DSP
15B 1.99	R				

SHOP SHIFT CREW	FAIL	CRT ACT	ELAP	MHRS	DATE	TIME	LOC	ACTION TAKEN
AED	300	22	5	10	032078	1400		See VSR #

15413. ATC power supply was adjusted to 28V from 26.5V

Stephenson / [illegible]
SIGNATURE

M A C T 2

HDW-ID S/S A S/A	METRO PART NUMBER	SN-ON	SN-OFF	QTY	DSP
	R				

SHOP SHIFT CREW	FAIL	CRT ACT	ELAP	MHRS	DATE M M D D Y Y	TIME	LOC	ACTION TAKEN

SIGNATURE

M A C T 3

HDW-ID S/S A S/A	METRO PART NUMBER	SN-ON	SN-OFF	QTY	DSP
	R				

SHOP SHIFT CREW	FAIL	CRT ACT	ELAP	MHRS	DATE M M D D Y Y	TIME	LOC	ACTION TAKEN

SIGNATURE

CONT D

ORG	APRNT FAIL	START DATE M M D D Y Y	START TIME	REMARKS:

STOP DATE	STOP TIME	ELAP	MHRS

SIGNATURE

DEFERRED CODE	EST TIME	DATE M M D D Y Y	TIME	REMARKS:

TEST

TEST	APRNT FAIL		DATE	CLOSE TIME
230	910	ATC power supply check 28V	032078	1530

ELAP	MHRS	SUP-OK	SIGNATURE
2	4		[illegible]

FIGURE 3-4. VEHICLE SERVICE REPORT: INCIDENT 168, MARCH 17, 1978 (Sheet 2)

The forms described above constitute the major elements of the existing operations management information system. Other WMATA logs of various types are kept for security incidents, safety incidents, power, and periodic station system status. WMATA considers these to be separate issues with usually minimal impact on overall system operations and with second-order small-incident rates compared to the number of VSR's initiated. When these types of problems do impact on operations, they also appear on the Summary of Train Operations log.

From the passengers' point of view, however, train operations are just one aspect of overall system service. Escalator and fare collection outage incidents also strongly influence passenger perception of service and should ideally be tracked just as conscientiously and be restored just as quickly as train incidents. This was not being done during the time of this study.

Recommendations

The major recommendations regarding the WMATA management information system are that WMATA:

1) automate their management information system to facilitate more extensive analysis conducive to formulating, implementing, and verifying service improvements and maintenance cost reduction actions; and

2) expand it to keep track of escalator and fare collection equipment outages as conscientiously as train incidents.

Lessons Learned

The major lesson learned from the WMATA experience for developing properties to heed is that an automated management information system should be designed, developed, and in place as early as possible, preferably before the first new vehicles arrive on the property, and it should be continuously used thereafter. All aspects of equipment requirement verification testing, warranty provision, product improvement prioritization, etc., should be anticipated aspects of such a system. Although manual data capture may seem adequate initially, the rapid growth of large numbers of records, reports, forms, etc., soon overwhelms any manual analysis efforts. It is also easier to buy various pieces of the system as parts of equipment procurements (vehicle, ATC, communications, etc.) with acquisition money rather than try to buy it later out of operating funds.

4. ASSESSMENT OF METRORAIL SYSTEM

4.1 DEPENDABILITY AS A HISTORICAL MEASURE OF SYSTEM HEALTH

Background

The process for keeping daily account of train trips completed and train trips scheduled for the WMATA Metrorail System is described in Section 3.3. The ratio of these two quantities is a measure of overall system dependability or "transportation service" that has been computed and used for WMATA management review purposes since the Blue Line opened on July 1, 1977. Table 4-1 shows this ratio as a monthly average percent for both the Red and Blue Lines.

TABLE 4-1. MONTHLY AVERAGE DEPENDABILITY PERCENTAGE

Month	MONTHLY AVG. PERCENT Red Line	Blue Line
July 1977	94.5	79.8
August	95.7	92.2
September	97.0	93.1
October	97.4	95.0
November	97.8	96.5
December	98.3	97.3
January 1978	98.4	98.2
February	97.5	97.3
March	98.3	98.2
April	98.7	98.2
May	98.7	99.1
June	96.7	99.1
July	98.7	96.5
August	98.2	98.2
September	98.2	98.2

This table shows the initially low service, but then rapidly improved service after the July 1, 1977 opening of the Blue Line, a gradual trend of improvement on the Red Line, a slight dip in performance due to the Red Line extension opening in February, 1978, and a converging equivalent level of service on both the Red and Blue Line since March, 1978.

The Port Authority Transit Corporation (PATCO) rail rapid transit system has historically measured the percentage of scheduled trips which arrive at their intended destination terminal within four minutes of schedule. (They have since changed to a five minute threshold.) This same combined availability/dependability measure can also be gleaned from New York City Transit Authority (NYCTA) train delay data. Therefore, in an attempt to compare WMATA with at least these two other systems, this definition of transportation service (more stringent than what WMATA currently uses, as discussed in Section 3.3) was applied to a small sample of WMATA Red and Blue Line data (first ten operating days of March, 1978). Any train off-loaded anywhere between terminals or delayed four minutes or more enroute was counted as an aborted train. The result was the reduced performance numbers as shown in Table 4-2.

TABLE 4-2. DEPENDABILITY MEASURE COMPARISON (TWO-WEEK SAMPLE)

	WMATA Standard Definition	PATCO Definition Applied to WMATA Data
WMATA Red Line	98.8%	98.3%
WMATA Blue Line	97.9%	97.0%

It is estimated that application of this more stringent availability/dependability definition to the last nine months of data in Table 4-1 would reduce each entry by about 0.8 percent and proportionately more for earlier months.

On the average then, a conglomerate number for the nine month period for both lines of WMATA would be about 97.2 percent. The corresponding PATCO system number is typically about 98 $\pm$ 1 percent depending on the time of year. The corresponding NYCTA total system number is currently between 97 and 98 percent.

Therefore, a reasonable overall conclusion is that WMATA's transportation service at the systemwide operational level is currently at least comparable with PATCO and NYCTA as representative of the full gamut of other U.S. rail rapid transit systems.

The reader should recognize the limitations of the small WMATA data sample and approximations used, the potential for error in attempting to apply a different definition of dependability to those data, and the numerous physical and operational differences in the system configurations being compared. The reader should also appreciate that one measure of dependability does not tell the whole story. However, this one measure with all its limitations, or at least the one WMATA has been using, should continue to be utilized to measure relative change.

And, as will be shown later in this report, correction of just a few major detrimental problem areas has the potential for a major improvement in WMATA dependability. It is estimated that a 50 percent reduction in only three particular categories of off-normal incidents (eliminating only 11.1 percent of the total set of typical daily off-normal incidents) could increase the current WMATA dependability from 97.2 percent (PATCO definition, five-month conglomerate number) to about 98.2 percent, an excellent number for the rail rapid transit industry as a whole. This corresponds to improving the WMATA definition number, currently running about 98.2 percent, up to about 98.8 percent.

Recommendations

The major recommendation stemming from this analysis is that WMATA consider changing to the more stringent PATCO-type definition of availability/dependability as being more compatible with the rest of the industry. It is also recommended that WMATA participate in an ongoing effort by NYCTA, Port Authority Trans Hudson (PATH), Toronto Transit Commission (TTC), and others who are attempting to converge on common definitions for reporting system performance measures.

Lessons Learned

Further reflection on the data of Table 4-1 suggested that considerable "lessons learned for developing properties" can result from a detailed analysis of the monthly dependability percentage for the Red Line dating back to its opening day, and daily dependability percentage data for the more rapidly changing situations of the Red Line opening, Blue Line opening, and Red Line extension opening. WMATA's experience in the introduction of new lines can be important for helping new properties predict what should happen as they open or extend lines under their own particular circumstances.

Table 4-3 shows the gradual improvement of the Red Line performance from opening day on March 29, 1976 and a marked dip in performance when the Blue Line opened on July 1, 1977. (Red and Blue Line data for July through September 1977 are repeated from Table 4-1 for reader convenience.) This dip is because the two lines are strongly linked by the connector track and the availability of only the Brentwood Yard (on the Red Line) for service, inspection, and unscheduled maintenance of vehicles. (The Red Line was in essence sharing the Blue Line's problems in July, 1977.)

Figure 4-1 shows the daily dependability percentage for the first two months of Red Line Operation. Of particular interest is the relatively constant performance throughout the period with the daily dependability percentage data containing little more information than the monthly average data of Table 4-3.

Figure 4-2 shows the dramatic impact of the Blue Line opening on overall system performance (tripled the system's total length, vehicle needs, and operations and maintenance personnel needs). The Blue Line's first two months of performance were significantly lower than was the Red Line at its opening. However, things settled back to a more gradual improvement rate with the Blue Line performance converging toward the more constant Red Line performance after September 1977.

Daily dependability data for the Red Line extension opening of February 6, 1978 are not shown because it is difficult to see much change at all because of the opening. WMATA was especially prepared and cautious after their Blue Line opening experience. The relatively poor dependability for the early days of the week of February 6 on both lines was because February 6 and 7 were the days of the "Great Blizzard of 1978."

TABLE 4-3. MONTHLY AVERAGE DEPENDABILITY PERCENTAGE SINCE RED LINE OPENING

MONTH	MONTHLY AVG. PERCENTAGE RED LINE	BLUE LINE
March 29 - April 5, 1976	Not Avail.	
April 6 - 30	92.0	
May	92.6	
June	Not Avail.	
July	96.5	
August	98.5	
September	99.3	
October	98.1	
November	98.9	
December	95.0	
January 1977	96.9	
February	98.3	
March	98.9	
April	98.9	
May	98.7	
June	97.2	
July	94.5	79.8
August	95.7	92.2
September	97.0	93.1

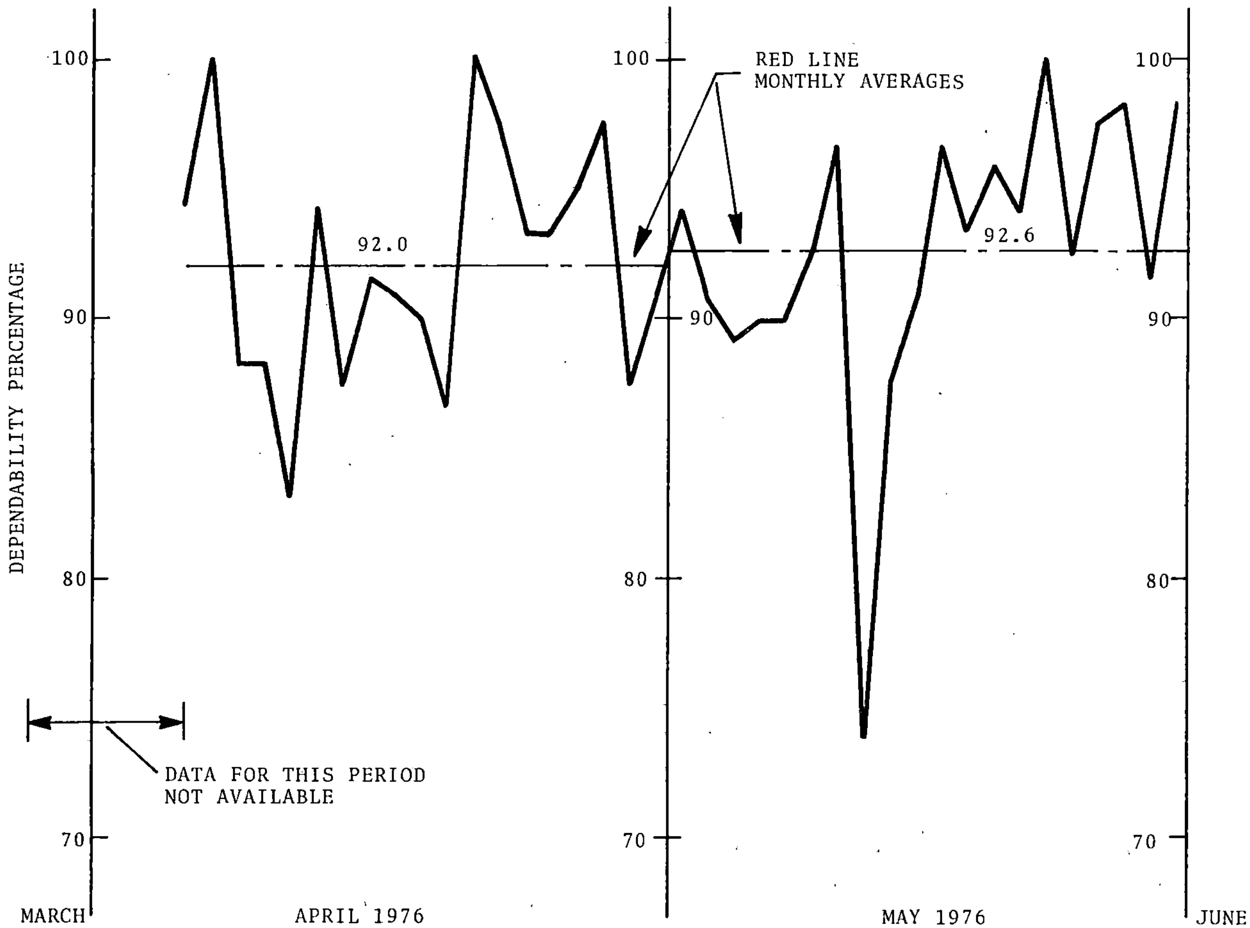


FIGURE 4-1 DAILY DEPENDABILITY PERCENTAGE FOR FIRST TWO MONTHS OF RED LINE OPERATION

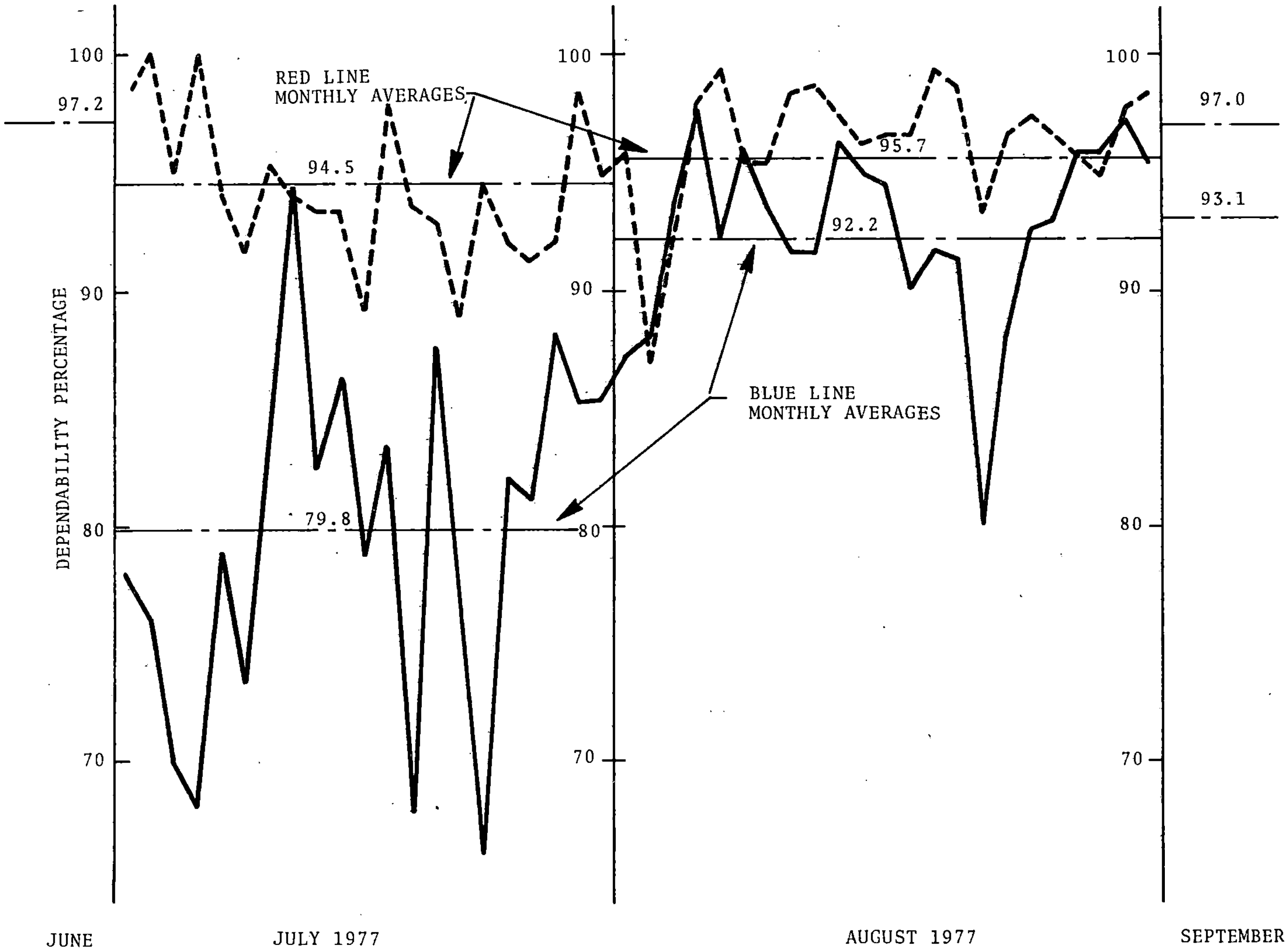


FIGURE 4-2 DAILY DEPENDABILITY PERCENTAGE FOR FIRST TWO MONTHS OF BLUE LINE OPERATION

In a similar vein, any daily measure can be misleading without carefully looking at the cause of each incident and supporting special reports. Many incidents are "people" and "environment" type problems and others are infrequent unusual occurrences which have nothing to do with equipment failures and are beyond the control of the property (sick passenger, smoke from fire abutting guideway and obscuring vision, etc.).

The "primary" lessons learned from the WMATA experience for developing properties to heed are the following:

1) Preestablish and consistently use a good measure(s) of availability/dependability (preferrably starting during prerevenue testing operations) that are compatible with the transit industry norm for such measures from opening day.

2) The measure(s) should ideally have a predicted value (which can then be verified through revenue testing) methodically linked to the following: overall system design, reliability and maintainability requirements of the various subsystems (particularly the vehicle and automatic train control system), system effectiveness attributes of the vehicle, failure recovery procedures, etc.

3) Such measures are a very good daily, weekly, and monthly average indicator of the rate at which transportation service is changing due to new line section openings, other similar major events, and gradual improvement in reliability or failure recovery procedures. However, detailed study of individual incidents via their supporting reports are necessary to develop an understanding of what is really happening and to separate people- and environment-type problems from equipment failure problems.

4) Central controllers will learn how to maximize the dependability measure by their actions. It is therefore important that the measure used properly reflect management's desired transportation service objectives.

4.2 EVALUATION OF SYSTEM DEPENDABILITY CONTRIBUTORS

Background

The orginal program plan for the WMATA assessment project stated that "The emphasis of this assessment will be on the operational hardware and the effect of malfunctioning or unreliable equipment on transportation service." As a result of discussions between TSC and the General Superintendant Rail, Transportation Department; Command Center Assistant Superintendent; and Training Instructors of WMATA, and subsequent analysis by TSC of various WMATA data, this section:

1) characterizes the effect of malfunctioning or unreliable equipment on WMATA's transportation service,

2) prioritizes those categories of malfunctioning or unreliable equipment which have the highest impact on WMATA's transportation service,

3) recommends follow-up action conducive to improved transportation service, and

4) outlines major areas of lessons learned that should be disseminated to rail transit properties currently under development.

In order to characterize the effect of malfunctioning or unreliable equipment on WMATA's transportation service, an analysis was made of the daily "Summary of Train Operations" sheets (See Figure 3-2 example) for the first ten days of March, 1978 Red Line operation. The findings are summarized in Table 4-4. In particular it was found that:

1) There were 126 incidents recorded in 13 (of 18 pre-established) "problem categories" (see headings in Figure 3-3 example) from among 2431 scheduled trips.

2) All but five of the 126 incidents eventually resulted in some form of unscheduled vehicle maintenance action.

3) Only 39 of the 126 recorded incidents resulted in an aborted trip and/or passenger delay of at least two minutes.

4) Only 19 of these 39 delaying or aborting incidents resulted in all 29 of the aborted trips. (Only 15.1 percent of all incidents resulted in aborted trips, the only parameter used in the WMATA dependability measure.)

5) Three categories of incidents constituting only 22.2 percent of the total (126) incidents resulted in 72.3 percent (the vast majority) of the train aborts, 52.9 percent of the passenger delay time, and 58 percent of the train delay time. These three highest priority problem categories were BRK LIGHT, LOSS SPD RDOT, and BRK AIR PRES, in descending order of priority.

6) Four categories of incidents constituting 29.4 percent of the total (126) incidents resulted in 27.7 percent (the remainder) of the train aborts, 40.9 percent of the passenger delay time, and 36.2 percent of the train delay time.

7) Six categories of incidents constituting 48.4 percent of the total (126) incidents resulted in no train aborts, only 6.2 percent of the passenger delay time, and only 5.8 percent of the train delay time.

TABLE 4-4. EFFECT OF MALFUNCTIONING OR UNRELIABLE EQUIPMENT ON TRANSPORTATION SERVICE (CATEGORY PRIORITY)

Priority	Category from Daily Summary Rail Operations	% of Total Incidents	% of Trips Aborted	% Pax Delay	% Train Delay
High	BRK LIGHT	6.3	37.9	21.2	33.9
High	LOSS SPD RDOT	13.5	24.1	22.6	9.4
High	BRK AIR PRES	2.4	10.3	9.1	14.7
Medium	ATC PROPL	12.7	13.8	8.4	11.1
Medium	BRAKES	4.8	6.9	9.9	6.9
Medium	SIGNAL	2.4	3.5	5.5	7.4
Medium	MISCELLANEOUS	9.5	3.5	17.1	10.8
Low	LOSS PROP PR	1.6		3.6	4.2
Low	DOORS	10.3		1.5	0.9
Low	LONG SHORT STOP	7.9		1.1	0.7
Low	MTR OVERLOAD	21.4			
Low	RADIO	4.0			
Low	ENVIRONMENTAL	3.2			

The 13 problem categories of malfunction or unreliability, in descending order of highest detrimental effect on transportation service, are listed in Table 4-4 and ranked in groups of "High, Medium, and Low" priority consistent with groups 5), 6) and 7).

Although only a small sample of WMATA data was used to derive these results, a brief scan of additional data in the same time frame indicated that duplication of the analysis on a much larger sample of data would result in similar trends of priority problem categories. These trends may have changed, however, based on presentation of this information to WMATA in June, 1978 and subsequent WMATA action.

By focusing their attention on, and making a 50 percent improvement in, the three high-priority problem categories of Table 4-4, WMATA would increase the April, 1978 dependability level for the Metrorail system from 98.2 percent up to about 98.8 percent. Two of the problem areas studied by the review team, namely the ATC Power Supply Failures and the Leaking Brake Control Valves, have a strong correlation in alleviating the three high-priority problem categories of Table 4-4. (These two problem areas are discussed in Section 5.3 of this report.) The majority of other problems treated in this report have less impact on system dependability, but are more important for reducing the frequency of high-incident categories (such as door problems) or for potentially reducing maintenance costs (such as the wheel/rail wear problem).

Recommendations

It is recommended that a more vigorous, organizationally-coordinated operations, maintenance, and training attack be made on the high-priority categories of problems identified in Table 4-4 by using the following approach:

1) Separate the high priority categories of problems into subcategories by detailed analysis of the corresponding "Vehicle Service Reports" (see Figure 3-4 example) of the resulting unscheduled maintenance actions.

2) Examine alternative "fixes" intended to reduce the frequency of occurrence of the incident; increase the diagnostic or cutout capabilities of the train operator (equipment or training) to minimize the impact of the incidents when they do occur; or change the operational criteria for off-loading or delaying a train using different failure management strategies.

3) Better utilize the carborne monitoring equipment for diagnosis of vehicle and automatic train control system problems.

4) Consider adding more information to the existing reporting forms/procedures to make them more conducive to incident analysis and management information system tracing of incident actions.

5) Implement selected fixes and evaluate their impact on revenue service by continuous analysis and tracking of all incidents.

6) Automate the management information system to ease the analysis process especially as the residual priority problem trends become harder to separate out.

The above analysis and recommended attack on the problems identified assume that the train operators and central control operators have been fully trained and currently utilize all diagnostic information, on-board cutout capability, and track layout features available to them within the bounds of the safety and operating rules and the current 5- and 6-minute minimum scheduled headway situation. Of course there have been periods of time when this assumption has faltered and the initiation of any newly trained operator into revenue service challenges the assumption again. Meanwhile, the WMATA training personnel seem to have squeezed every drop of empirically derived diagnostic indication (such as sequence or combination of feasible lights that are lit) out of the inherent nature of the vehicle and ATC system and incorporated it into the training process.

Though WMATA's capability of on-board diagnostic and failure indication equipment is comparable to other transit properties, it is recommended that the number, relative placement, and function of vehicle-borne indicator lights, trouble lights, circuit breakers, hand brake, cutout levers, etc. of the existing vehicle and the new vehicle procurement specification be objectively reexamined. This reexamination should be conducted by a panel of engineering, operations, maintenance, and training personnel to see if any improvements can be made (based on operating experience to date) relative to subsystem reliability requirements and the impact of these features on minimizing delays and trip aborts.

Sometimes the relatively inexpensive and simple addition of the right level or clearer indication of fault indication can better utilize the inherent redundancy of multiple cars in a train and thereby avoid certain categories of train aborts. For example, the BRK LIGHT category of malfunction from Table 4-4 causes 37.9 percent of all aborted trips with only 6.3 percent of the malfunction incidents. Perhaps another layer of more definitive fault isolation and/or correspondingly more convenient cutout should be designed to offset this problem.

Lessons Learned

The primary lessons learned for developing properties to heed are similar to those which have been preached elsewhere in the last few years:

1) There will always be some portion of delaying incidents attributable to people and the environment (not malfunctions) which should be predicted from empirical measurement of operating properties.

2) Design of the vehicles' "system effectiveness attributes" (cutout capabilities, diagnostics, utilization of inherent redundancy in a train, etc.) is extremely important to achievement of a high value of system dependability.

3) A system level methodology must be developed during the design process to link the above factors with subsystem requirements in procurement specifications, i.e., mean time between failures, mean time between service interrupting failures, mean time to restore and mean time to repair.

4) An automated management information system should be in place and operative as a diagnostic tool before delivery and check out of any major subsystem.

5) Although early analysis of all problems should easily indicate those which most effect revenue service, more sophisticated (automated) analysis is generally required to properly prioritize reappearing problems after the stand-out problems have been addressed. Such analysis should weigh the impact on service, recurring maintenance cost, acquisition cost to make a change, and anticipated benefit of proposed change.

5. STATUS OF VEHICLE SUBSYSTEM

5.1 TECHNICAL DESCRIPTION OF VEHICLE

When the Washington Metropolitan Area Transit Authority (WMATA) began operations on March 29, 1976, its schedule called for 24 cars. At the time of this study, operation on sections of the Red and Blue lines required a schedule of 196 cars. In November of 1978, a section of the Orange Line to New Carrollton opened which required an additional number of cars. There are also several additional lines presently under construction.

To date, all of the original order of vehicles from Rohr Industries has been received (300 vehicles). WMATA has just completed a draft specification for additional cars to supplement their present fleet. These additional cars will be required to meet operating schedules when new lines are opened for revenue service.

The WMATA cars are 75 feet long and 10 feet wide and have a floor-to-ceiling height of 6 feet 10 inches in the center of the car and 6 feet 4 inches under the evaporators at each end of the car. These cars are of the "A" and "B" car married-pair concept, semi-permanently coupled. The "A" car contains the train control equipment and the air compressor, while the "B" car contains the low-voltage power supply and the battery. Empty, each car weighs 72,000 pounds and has a seating capacity of 80. Crush capacity is 220 passengers.

Car Body Structure

Metro's transit car bodies are of semi-monocoque design and are constructed primarily of aluminum. The main underframe consists of aluminum beams and intercostals attached to side sills, while the rod frame is made of low-alloy, high-tensile steel.

The side wall is constructed of aluminum extrusions attached to the vertical frame extrusions, which are riveted to the horizontal side sill extrusions running the length of the car. The roof is constructed of riveted aluminum. The rear end of the car is also formed of aluminum extrusions, while the front end is molded fiberglass. The floor is constructed of aluminum-faced plymetal panels except for the entranceways, where the plymetal panels are stainless-steel faced. Fiberglass insulation separates the floor from an aluminum subfloor.

Trucks

The trucks are of a side bearing design with a double reduction, parallel gear drive. The car body is supported on the bolster through an interface between two stainless steel pads on the body and two side bearing pads on the truck bolster. There are two air springs on each truck located between the truck's frame and bolster. There is one leveling valve for each "F" end truck air spring. A single leveling valve controls both air springs on the "R" end truck. The air springs maintain a car floor height of 40 inches above the running rail at all times regardless of load. The wheels are 28-inch, class-C, wrought steel with a cylindrical tread contour.

Coupler and Drawbar

The "F" end of the car has a hook-type mechanical coupler that can lock or unlock either manually or remotely from any cab. The "R" end has a semi-permanent drawbar which is fixed at the "A" car to prevent rotational movement. The draft gear of the coupler and drawbar is designed to have buff strength of 125,000 pounds. If this limit is exceeded the shear bolts release and allow the coupler or drawbar to telescope and engage the anti-climbers.

Side Doors

On each side of the car there are three bi-parting doors that slide into door pockets creating a 50-inch door opening. Each side door panel is of honeycomb construction with an aluminum inner and outer skin and is mechanically linked by an adjustable connecting rod to an electric door operator. The door operation is controlled by two pairs of trainline wires, one pair for each side. Polarized signals are applied to the door control trainlines to open or close the doors. A motion detection device is utilized, so that a door-open signal cannot be generated if the train speed is over 2 mph.

The door circuitry provides for a sensing circuit capable of detecting an obstruction up to 3/8-inch thick. The obstruction detection is based on the failure of the door to close within a specified time. Upon detection, both panels of that particular door will recycle once. If the obstruction is not removed on the second closure attempt, the door will close despite the obstruction, but the train cannot move due to the inability of the door interlock circuit to establish power to the master controller. However, due to irregularities in the detection system, the system's obstruction sensing circuitry is presently disconnected. A pushback feature is also incorporated into the door mechanism which will allow each door panel to be pushed back 1-1/2 inches to release a person or object that might be trapped.

Lighting

Fluorescent lighting is utilized throughout the interior of the the car and uses either a single- or two-lamp static ballast concept. This lighting system operates on two main and one emergency battery circuit. The emergency circuit connects three staggered fixtures. During a low voltage power supply failure, the fixtures remain energized from the battery through a load shedding device.

Interior, Windows, and Seats

Each car's interior lining is an acrylic-polyvinyl chloride (PVC) alloy which is vacuum-formed to greatly reduce the number of joints. This material was chosen for its resistance to fire and vandalism.

The floor is covered with synthetic, cushion-backed wool carpeting. The carpet is bonded to the floor with an adhesive except in the entryways where it is easily removable.

The operator's cab floor is covered with a cushioned rubber mat.

Side windows are double-glazed with a fixed breather. The outer layer is 1/4-inch, clear, abrasion- and mar-resistant acrylic, and the inner layer is 1/4-inch, laminated, tinted glass. The operator's window is 9/16-inch, clear, laminated glass backed with 1/4-inch abrasion- and mar-resistant acrylic sheet.

All transverse seats are cantilevered, except for four back-to-back, two-passenger seats which provide space for equipment wells. Besides being attractive, this arrangement allows for more efficient floor cleaning. The seat cushions are vinyl-covered neoprene for fire retardancy.

Destination Signs

On each car there are two destination signs on each side, and one on the front of the car over the end door. These signs are controlled by a binary-coded decimal signal from seven trainline wires. This signal is checked by an integrated circuit comparator with the binary-coded decimal signal produced by the curtain positioning sensor. The comparator output rotates the motor in the direction that allows the signal from the curtain position sensor to match the command transmitted by the trainline.

Propulsion

Each car has four 175-hp, 325-Vdc, 2450-rpm continuous-rated, self-ventilating traction motors. Each motor is resiliently attached to the parallel drive gear unit. The gear ratio of 5.414:1 gives a maximum speed of 75 mph with fully worn wheels. The train can achieve a maximum speed of 75 mph in 23 seconds at full seating capacity.

The car has three acceleration rates ranging from 0.75 to 3.0 mph/sec with a passenger load of 24,000 pounds and five deceleration rates ranging from 0.75 to 3.0 mph/sec with a passenger load of 33,000 pounds.

The propulsion control equipment is an advanced, air-operated cam controller system with a separate controller for power and dynamic braking. This limits the rate of change of acceleration to a maximum of 2.0 mph/sec/sec and limits rate variation during acceleration or deceleration steps to a maximum of 0.6 mph/sec/sec.

Motor current is sensed through three current transducers: two in the power circuit and one in the dynamic braking loop. This signal is compared with the logic-designed levels on the current limit curcuit, and the output of that comparison controls the cam controller's movement.

There are three motoring rates, a coast mode, and four dynamic braking rates. For added protection to the traction circuit, a ground fault detection circuit has been designed into the system.

The logic control for the propulsion equipment consists of 10 printed circuit boards. Two independent circuits in the propulsion equipment assure power removal upon receipt of a command. The first is through normal speed-time related circuits which override the jerk-limited retrogression, if the power is not removed within the specified time for that speed.

Friction Brakes

The friction braking system for these cars is hydraulic and responds to digital commands received from four rate trainline wires. Final friction braking is by means of 20-inch discs and hydraulically operated brake pads, mounted outboard of each wheel.

Each truck has its own brake control valve and electronic control logic, consisting of five printed circuit boards and an accumulator. A single hydraulic power pump feeds both trucks. The braking system includes a differential pressure circuit with an indicator in the cab, which is activated if more than a 100-psi difference occurs between the brake cylinder pressure of the two trucks. Under these conditions the train cannot operate automatically and must be moved manually.

Each vehicle is equipped with a hand brake which is hydraulically applied, mechanically held and hydraulically released. This brake is hydraulically separate from the service brake system.

An independent pneumatic emergency braking system is available on each car. It may be either electrically or pneumatically applied by de-energizing the emergency magnet valve or venting the brakepipe through an emergency exhaust valve, respectively.

A separate slip-slide control on each truck can detect a speed differential of 2 mph or more between axles. Axle accelerations of

8 mph/sec or more for speeds above 3 mph can also be detected by this control.

Attendant's Cab and Controls

The attendant's cab is full width to enable the attendant to monitor side door operations on either side. This cab contains the low voltage control circuit breakers for all subsystems except for the battery and motor generator output. There is a set of seven toggle switches sealed in the normal position at all times. These switches control the automatic or manual mode of door operations, the headlight bypass function, the power knockout, the automatic train protection cutout, the dynamic brake cutout, the door control trainline cutout, and the door interlock bypass. There is also a cutout switch to isolate the propulsion system of that particular car.

The attendant's auxiliary control panel contains a speaker, door control, environmental key switch, remote coupling and uncoupling control, buzzer, train light control, destination sign control, and right-side door control.

The attendant's console is situated directly in front of his seat. This console has two system monitoring panels. The upper panel contains the system status indicators such as the brakepipe and brake cylinder gages and the system status lights for monitoring doors, brakes, and program station stop. The lower panel contains the Automatic Train Operation (ATO) stop and start buttons, the energization key switch, and the mode direction switch. The manual master controller and emergency and recharge buttons are also on this panel.

There is a third panel for communications, which contains control for volume control, radio, public address, and intercom.

Vehicle Communications

The vehicle communications include the onboard mobile radio, public address system, and passenger attendant speaker.

Four frequencies are approved by the proper authorities and utilized on Metro's radio communication system, two of which are assigned for operation, one for maintenance, and the fourth for security.

The carborne mobile radio system is capable of generating two types of calls, normal and urgent, by depressing separate buttons on the operator's console. The urgent call transmits an overriding 1500 Hz signal to the base station, while the ordinary call transmits a 1000 Hz signal. The control logic is designed to give precedence to the urgent call over other traffic.

Carborne Monitor

A carborne monitor (CBM) exists on each married pair, which presently records a number of critical system parameters within the married pair and at the vehicle/wayside interface (including additional capacity to monitor others as required). The CBM recorder has two channels using a 30 minute continuous loop. One channel is analog and includes the Automatic Train Protection (ATP) speed commands transmitted by wayside. The second channel consists of digital time division multiplexed data for monitoring critical vehicle subsystem parameters (including Automatic Train Control (ATC), propulsion trainlines, door trainlines, etc.). All data being recorded on each CBM are trainlined throughout the train and are available at the Daily Safety Test (DST) receptacle in each vehicle cab for monitoring during test runs and revenue operation.

Heating, Ventilating, and Cooling

The vehicle environmental control system consists of two evaporator-blower units located in the low ceiling area at each end of the car, the overhead heater elements, which are located adjacent to each evaporator, the floor heater elements, the refrigerant compressor, and two condenser fan units under the vehicle.

The heating subsystem is provided through 28-1/2 kW of overhead heating capacity and 17-1/2 kW of floor heat. The overhead heaters are protected, in the event air circulation is stopped, by an air flow sensing switch connected to the overhead heat contactor, a thermostat adjacent to the heater element that is connected to the shunt trip of the overhead heat circuit breaker, and by a fusible link in the feed to the heater element. The overhead heat is arranged in two stages to provide efficient operation during the reheat and normal heating cycle.

The capacity of the heating element is such that with an ambient temperature of 5°F an average interior temperature of 64°F is achieved.

A separate heater-defroster unit is provided in the cab, to ensure the operator's windshield is clear at all times and to maintain the temperature in the operator's compartment.

Ventilation of the car is accomplished by the evaporator-blower fans which provide over 1400 cfm of fresh air to the car.

The cooling system, which has a tested capacity of 14.6 tons, consists of two independent refrigeration systems with the exception of a shared compressor.

5.2 CURRENT STATUS

During this assessment of the carborne subsystems, there was an opportunity to evaluate the total car in the Brentwood Maintenance Shop and in revenue service. The overall car lines are trim, and the interior decor warm and inviting. The operation is smooth, and with the exception of wheel squeal around curves and an occasional noise from brake application, the ride is quiet. The vehicles are clean, well-lighted, have easily distinguishable location and destination signage, and show no visible evidence of vandalism.

The vehicle is well-maintained, but due to the high degree of sophisticaion of some of the subystems, such as the hydraulic friction brakes and the ATC power supply, there were many "burn-in" problems, many of which have been corrected, but some still to be resolved.

WMATA attacked the problems of car equipment failures head-on. Several separate failure investigations were conducted simultaneously. Many failure problems had to be resolved within a short period of time. In some cases the resolution of the problem was handled by a high level of maintenance while the real solution had yet to be determined.

There are two exceptional problems that require excessive maintenance which, unless resolved before any further extensions of the line are opened, could result in train shortages just when the timetable will call for additional trains to provide this extended service. These are excessive wheel flange/rail wear and excessive friction brake disc and pad wear. Also there are several aggravating door problems still plaguing the system such as the door motor control relay malfunctioning, loose door limit switch mountings, and door sticking. These problems cause delays due to the inability of the train to receive a signal to proceed. The leaking brake control valve still requires trains to operate manually when this problem arises. The carborne monitor, installed in each car, is a diagnostic tool that can greatly enhance the resolution of many failures and reduce the maintenance effort. However, although operational, its outputs are not used as a means of reducing downtime and repair costs. The ATC power supply, the heart of the train control system, has an exceptionally high failure rate, a failure that results in a train's inability to continue under automatic operation; in which case, the train would be required to proceed under manual operation to the next station, discharge passengers and proceed to a maintenance area.

5.3 KEY PROBLEM AREAS

5.3.1 Introduction

After investigating many problems in the equipment area, the review team determined that the following problems, in their opinion, have the most impact on service, operation and maintenance costs:

1) Excessive Wheel Flange/Rail Wear
2) Excessive Wear of Friction Brake Disc and Pads
3) ATC Power Supply Failure
4) Intermittent Malfunctioning of Door Motor Control Relay
5) High Adjustment Rate for Door Limit Switches
6) Carborne Monitor Underutilization
7) Leaking Brake Control Valve.

The following sections present the key problem areas in the following format, where practicable:

1) Background
2) Review Team Action/Findings
3) Recommendations
4) Lessons Learned.

5.3.2 Excessive Wheel Flange/Rail Wear

Background

One of the most costly vehicle problems confronting the Metrorail system is that of excessive wheel flange/rail wear. With vehicle mileage rapidly accumulating on the system, particularly due to increased service and system expansion, the wear problem has become serious relative to its significant impact on maintenance costs and its potential impact on system availability. One gross indicator of the severity of the problem is the fact that WMATA, of the time of this study, is averaging about 35,000 miles between wheel trueings, where a recent survey of other properties indicates their experience to be between 100,000 and 125,000 miles between trueings. Also, in contrast to other operating properties that generally average about 10 years between rail replacement, WMATA must consider replacing rail in the near future at a few specific locations on the Blue Line (curved track, special-work track), a line that has been in operation only since July 1977. This wear pattern is causing a higher frequency of maintenance with its related higher expenditure of time, effort, and money. Car availability also can become a problem.

There are two areas of consideration that must be explored to determine the causes for this excessive wear problem: the design and construction of the truck and its dynamic interface through force and load relationships to the rail, and the construction of the roadbed and its reaction to the forces/loads produced by the truck.

WMATA's earlier thoughts were that cylindrical wheels, specified in their purchase of cars as a means to minimize hunting (as compared to tapered wheels), might be a contributor to the wear problem. They have equipped several cars with tapered wheels in order to determine the merits of the tapered wheel in reducing the wear problem. To date, not enough mileage has accrued to make a meaningful determination.

The standard wheel tread profile for the system is cyclindrical. The track was constructed with a 4-foot 8-1/4-inch gage on the tangent instead of the standard 4-foot 8-1/2-inch gage, and at certain curves has up to a 4-inch deficiency in super-elevation. At the time of this study there were no means on the system to equalize wheel flange wear by "looping" or "wying" trains. Also there were no flange lubricators on long curves or restraining rail on short curves and turnouts.

Review Team Action/Findings

With the excessive wheel flange/rail wear problem as critical as it is, the review team took a hard look into all aspects of the design and construction of the system including the track configuration and the vehicle. The review team initiated action to take rail profile tracings of selected areas of the Blue Line. As a result of this undertaking, it was determined that rail wear in these areas is significant and a more in-depth check of the system is required. Also, wheel profile tracings were taken of WMATA cars that were at the UMTA test track at Pueblo, CO. The wheel flange wear indicated by these tracings shows that these cars, operating exclusively on the track at Pueblo and thus not being influenced by the WMATA roadbed, have considerable flange wear for the low mileage accrued. This suggests that a truck dynamics problem exists and is contributing to the wear problem. In addition, three axis accelerometer tests were made on WMATA cars and NYCTA R-42 cars at the UMTA test track for wheel/rail load comparison. These tests indicate that there are high lateral accelerations on the WMATA truck as compared to the R-42 truck and strengthens the judgement of the review team that a truck dynamics problem is contributing to the wear of the wheel flanges and the rail.

In order to determine what contribution the truck makes to the wear problem, the review team discussed the problem with informed people within the Transportation Systems Center and with representatives of engineering laboratories who are knowledgeable in truck dynamic testing relative to wheel/rail force interactions and their measurement. With the information obtained at Pueblo, and from discussions with those people mentioned above, a finite series of tests is recommended to measure these lateral and vertical forces of the wheel. The results of these tests will give an indication as to what degree the dynamics of the WMATA truck contributes to the accelerated wear on the wheel flange and the rail.

Recommendations

In order to improve flange life, WMATA should consider executing the following measures which were not implemented either by design, choice, or monetary constraints.

1) Evaluate improvements of tapered wheels over cylindrical wheels relative to extended wheel flange life. If the tapered wheel does improve wheel flange life, the tradeoffs between flange life and ride quality relative to truck hunting must also be evaluated.

2) Implement a program for looping trains once the means for doing this is made available. By equalizing flange wear between each side of the wheelsets, a noticeable reduction in flange wear should be achieved within a short time span.

3) Although flange lubricators can be, if not used correctly, a source of skidding wheels and subsequent flat spots, they are used on many operating properties as a method of reducing galling between wheel flange and rail. WMATA should consider installing these lubricators on curves of greater than 500-foot radius where rail wear is evident.

4) Improve super-elevation in those locations where improvements are possible. Most of these locations are in the subway where, due to tunnel clearance problems, the appropriate super-elevation was not provided. (Any improvement, no matter how small, will reduce the force that the wheel flange imposes on the rail due to this deficiency in super-elevation. These forces in turn cause wheel flange and rail wear.)

5) Install restraining rail on curves of less than 500-foot radius. A restraining rail acts to reduce "crowding" of the wheel against the rail in these areas.

6) Consider realigning track to 4 feet 8-1/2 inches. The practice of using a 1/4-inch tight gage on tangent track, as adopted by some transit properties, is effective in reducing the amplitude of limit-cycle oscillations and the accompanying wheel/

rail force during hunting conditions. However, vehicle trucks operating with reduced effective flange clearances will be more susceptible to track-irregularity-induced hunting that with standard-gage track. Since no track is free of irregularities, the 1/4-inch tight gage can create more hunting problems and wheel flange/rail interaction than the standard gage. One possible approach is to conduct a test program wherein a designated area of track is realigned to 4-foot 8-1/2 inch gage and a comparison made of force and acceleration levels on the truck and rail prior to and after the gage has been changed.

Lessons Learned

There are many known and accepted practices that are utilized by the transit industry to reduce wheel and rail maintenance to acceptable limits, i.e., restraining rail, flange lubricators, etc. In the overall design of a transit system these practices should be seriously considered since past experience has proven that the advantages of such practices are cost effective. They should be accepted as common practice.

Truck dynamics are an individual property consideration since no two operating properties use trucks that are identical. Since most trucks are based on a design concept which is adapted to the individual operating property's requirements (e.g., wheelbase, disc brakes, etc.), the dynamic response to each type truck is different. No meaningful tests were set up to determine the dynamic response of the trucks provided for these cars.

Therefore, developing properties should include the following in their vehicle specifications and testing:

1) Dynamic analysis of truck design

2) Dynamic test of first article truck

3) Early wear and ride comfort measurement on property track.

When developing specifications for a transit system, attention should be given to conducting tradeoff analyses between safety, ride comfort, and performance, and the cost involved in achieving (capital costs) and maintaining (operating costs) adequate levels of these criteria. WMATA, with higher speeds and an intital concern for limiting hunting of these vehicle trucks for reasons of safety and ride comfort, is now experiencing the penalty of excessive wear and maintenance costs. More attention to the tradeoff and consequences of their initial design choices could possibly have been more cost-effective in the long run.

5.3.3 Excessive Wear of Friction Brake Discs and Pads

Background

The friction brake discs and pads have a relatively short life and require the vehicles to be out of service for friction brake maintenance more often than the industry norm. The short life can be attributed in part to the friction brake pad material and in part to the cycling of the propulsion system for speed regulation and programmed station stopping. Aggravating the problem is the fact that the B-1 brake position requires a friction brake application without the assistance of dynamic braking.

The service life experienced to date for the pads is 10,000 to 12,000 miles and 28,000 and 35,000 miles for the discs, which is unacceptable to WMATA. Under these conditions, it is estimated that it will take an expenditure of $3,000,000 to $4,000,000 per year to replace discs alone in addition to the cost for pads and labor involved, which severely drains maintenance funds.

The specification for the original 300 cars required that the friction brake pads have a service life of 2,500 miles under emergency conditions. There were no requirements for friction brake pad wear under normal braking modes. However, in the new specification for additional cars, the following is incorporated relative to friction brake life. "Brake discs and pads shall have service lives equal to or exceeding the following values:

1) With all braking by friction brakes: brake discs--30,000 miles, brake pads--2,500 miles;
2) With normal electrical plus friction braking: brake discs--200,000 miles, brake pads--40,000 miles."

WMATA is in the process of testing friction brake pads and discs from manufacturers other than the original equipment manufacturer (OEM). They are also testing pads of a different material composition, which have been supplied by the OEM. At this time not enough mileage has been accrued to make a meaningful determination. WMATA has requested, and Westinghouse Electric, the propulsion supplier, has responded with a proposal to modify a sample number of cars to utilize dynamic brakes in the B-1 mode. These modifications will be evaluated to determine if use of dynamic braking in the B-1 mode will reduce the friction brake wear significantly. At the time of this study, these changes had yet to be implemented.

Review Team Action/Findings

The review team has made several investigations into the ways and means of correcting this problem.

The team has acquired a tape from the carborne monitor of one car and has extrapolated from it the operating sequence of the B-1 brake mode. As an example, between Dupont Circle and Farragut North stations, the running time was recorded to be 74 seconds. Of this time, 15 seconds were with only the B-1 brake mode in operation, and of these 15 seconds, 10 seconds were above 30 mph. This example indicates that the vehicle is in the B-1 friction brake mode almost 20 percent of its running time between the two points mentioned. Friction braking during speed regulation accounts for considerable wear of the friction brake's pads and discs.

Recommendations

1) WMATA should, without delay, review the proposal made by Westinghouse Electric, and if acceptable, implement the change and evaluate it in terms of increased friction brake pad and disc life and also in terms of increased braking controller cam-switch-contact-tip wear. From this an evaluation can be made as to the tradeoffs between the B-1 brake mode with friction braking and the B-1 brake mode with dynamic braking.

2) Continue testing of alternative pad materials and evaluate, relative to longer life of the pad and disc, noise pollution and heat dissipation.

Lessons Learned

The fact that the specification for the WMATA cars spells out the emergency wear life and makes no mention of normal life cycle wear is a prime factor for the short life of the friction brake discs and pads. Also the failure to include temperature rise criteria in the specification is another factor for the short life.

The consequence of initially selecting a braking concept for better response time and shorter system control blocks (as a result) is now being experienced by WMATA through the penalty of excessive friction brake wear. It is essential that thorough tradeoff studies be conducted early in the design phase to understand consequences (both plus and minus) of design choices. The use of friction braking without dynamic braking in any part of the braking cycle, be it for faster response time or brake control cycling reduction, should be avoided or at least minimized. Using friction braking without the benefit of dynamic braking would make it difficult to specify a maximum temperature rise and therefore arrive at a meaningful life cycle for the discs and pads.

5.3.4 ATC Power Supply Failure

The ATC power supply supplies +28 Vdc to the ATC system located on each "A" car. This power supply has a high failure rate of power transistors (2N5686 and 2N5681). Over the past two years 64 such devices have been replaced. Failures of the transistors usually destroy other components; in particular, their base-emitter resistors burn and completely destroy the pc board.

The power supplies as manufactured by Safety Electric are poorly designed for use in this vibration environment. When they are brought to the shop for repair, they often have many loose connections ranging from open soldered joints to loose screws. An average of 6-8 hours is then required to repair the power supply in this condition.

The power supplies are not operating in the environment for which they were designed. Measured cabinet ambient temperature is 85°C, whereas Safety Electric designed for an ambient 65°C.

WMATA has had many discussions with Rohr, the car builder, and Safety Electric, the power supply manufacturer. Safety Electric has recommended to WMATA two modifications (input line filters and alternative output transistors). WMATA has not accepted these modifications because they do not address the total design deficiencies of this power supply.

Review Team Action/Findings

The review team has made an in-depth analysis of this unit and concluded that four out of seven desirable design features are lacking, namely: a means to prevent saturation of the power output transformer driving the load, a means to provide noncoincident base drive signals to the power output transistors, a means to generate nonoverlapping base drive signals to the bridge transistors, and a means to reduce the possibility of power supply failures due to vibration environments. These design features, if implemented into the circuitry, plus a better means of cooling the power output transistors, will greatly increase the reliability of this unit and reduce the number of failures.

Recommendations

WMATA should consider requesting Safety Electric to redesign the ATC power supply and incorporate the design features that are lacking as mentioned above. Safety Electric would have the option to accomplish this in-house or to solicit the power supply industry for a new design. It is also recommended that these design features be incorporated as ATC power supply requirements in the newest car specification.

Lessons Learned

There is no excuse for an electronic unit such as the ATC power supply to fail in such proportions. Properly designed, tested for the environment intended and with adequate quality control, these units should, with the exception of a few 'burn-in' failures, function trouble-free for many years.

In order for these units to function trouble-free for many years, it is imperative that the precise parameters under which they are to operate be known for its desired application. The fact that the parameters for the ATC power supply were a part of the car specification and not a part of the train control specification could have been a prime factor in the many failures that have occurred. The parameters described in the car specification may or may not meet the design criteria for the train control, once the train control is designed. The train control suppliers are best prepared to know what will be required to power their ATC equipment and should be responsible for its specification. The train control supplier should have overall responsibility for the interfacing of these equipments and not be subjected to split responsibility and be hampered by a piece of equipment improperly designed for its intended use.

Also the train control supplier, in his design of the equipment, would utilize the latest state-of-the-art design techniques. He would also take into consideration the operating environment of the equipment, moreso than a supplier whose only interest is one piece of equipment.

5.3.5 Intermittent Malfunctioning of Door Motor Control Relay

Background

There have been numerous instances where side doors failed to close. The cause of this failure had become a difficult problem for WMATA to diagnose since, in most instances, the problem would correct itself before the train was returned to a maintenance area. The door failing to close does not allow the train to proceed until corrective action is taken. This creates delays in service and reduces the availability of cars for revenue service. Fortunately, with only 196 out of a fleet of 300 vehicles needed for peak revenue service, this problem has not yet impacted the dependability percentage measure. After many frustrating investigations, WMATA maintenance personnel determined that the component responsible for this problem is the door motor control relay. WMATA had discussed this with Rohr Industries, the car builder, and Vapor, the equipment supplier. Many relays have been returned to the supplier for evaluation but nothing definitive has resulted up to now.

Review Team Action/Findings

The review team has inspected the area where the door operating equipment is mounted and observed that the door motor control relay is not completely sealed from the elements and is mounted in a location where dust and dirt can accumulate on it. The team also observed that the wipe of the relay contacts, due to inadequate contact pressure, was not sufficient to make positive contact when closed. The review team believes that this door motor control relay is not the proper relay for the environment and application.

Recommendations

WMATA should request of the car builder and equipment supplier that the present door motor control relay be replaced by a relay more suited for the application, one that is hermetically sealed and has sufficient contact wipe.

Lessons Learned

Matching the proper equipment to the application and environment is an essential task confronting those who are engaged in the design, approval, and ultimate operation of transit equipment.

It is extremely frustrating, costly in manhours and maintenence dollars, and compromising in car availability to attempt to make a piece of equipment function properly when it is not considered adaptable to the application intended.

There were no requirements in the car specification for the testing of subsystems and components of subsystems under proper environmental conditions before acceptance and installation in the vehicles. If this were a requirement, the supplier would have been required to demonstrate to the car builder and WMATA that the equipment would function properly. From the information gathered during this assessment it is apparent that the problem with this relay would have shown up during the environmental operating tests, and the need for a hermetically sealed unit would have been recognized.

5.3.6 High Adjustment Rate for Door Limit Switches

Background

WMATA has experienced a high rate of dead train and door problems that were traced to the adjustment of the LS1-5 door limit switches which, if not adjusted correctly, affect the door closing sequence and the traction interlock. They also discovered that the instructions given, when the cars first arrived, to adjust these switches were incorrect. All door-limit switches were then required to be readjusted. Once completed, the number of failures did not diminish significantly and readjustment of limit switches was still required.

Review Team Action/Findings

The review team observed the action of these switches and the method by which they were activated. It appears that the mounting brackets for these switches were fabricated from a thin material with much "give" to it, which created a movement that altered the switch adjustment after comparatively few cycles of door operation.

Recommendations

For evaluation purposes, WMATA should consider replacing the present door limit switch mounting brackets on several cars with one made of a thicker material. Should this modified bracket resolve the problem, a fleet retrofit would then be warranted. During this process, a more positive means of mounting this bracket can be investigated.

Lessons Learned

As mentioned previously, unless a component is adaptable and matched to its operating environment, its reliability is questionable. A requirement in the specification that each subsystem or component of subsystems be tested under proper environmental conditions would have brought to light the adjustment deficiencies of the door limit switches, and corrective action could have been taken before this equipment was installed on the vehicles.

5.3.7 Insufficient Utilization of the Carborne Monitor

Background

Each WMATA married pair is equipped with a Carborne Monitor (CBM) to record critical operating functions of the vehicles. At present, this system, which has an analog and digital channel, is recording data, but the data are not being used. The reason for this is that no hardware or procedures exist at WMATA to interpret Automatic Train Protection (ATP) command information on the analog channel or demultiplex the digital channel into a useful form. There have also been some initial hardware problems with these units, but their deficiencies have been isolated, solutions prepared, and a fleet-wide modification program initiated. A playback unit exists which plays back CBM data cartridges to verify proper operation of CBM units. A hardware/software processing and reporting capability has been specified as part of the new car procurement along with an expanded monitoring capability.

The potential system impact of an acquired capability in this area would address a number of generic problem areas including: 1) No Trouble Found Conditions (NTFs); 2) Problem Repeaters; 3) Transient conditions in an operational environment; and 4) Safety situations in accident/crash investigations and potential near misses (monitoring of ATP cutouts, etc.).

WMATA has instituted a modification program to correct CBM hardware deficiencies. A "click-on" feature has been added to solve a voltage level build-up problem at equipment turn-on. The modification program was 40 percent complete as of August 1978. In addition, a serious CBM trainline interfacing problem exists. Multiple CBM fault conditions in a train consist produce excessive voltages on CBM trainlines and burn out distribution transformers supplying CBM signals to the Daily Safety Test (DST) receptacle in the cab. Upon identifying the problem, a fix was designed, and CBM units unplugged until the required modifications could be made. A modification program has been planned but, as of yet, has not been initiated. It is suspected and supported by several test runs that the majority of these transformers in the fleet may be burned out. The resulting situation is that CBM data is neither recorded in the unit nor available at the Daily Safety Test (DST) receptacle.

Review Team Action/Findings

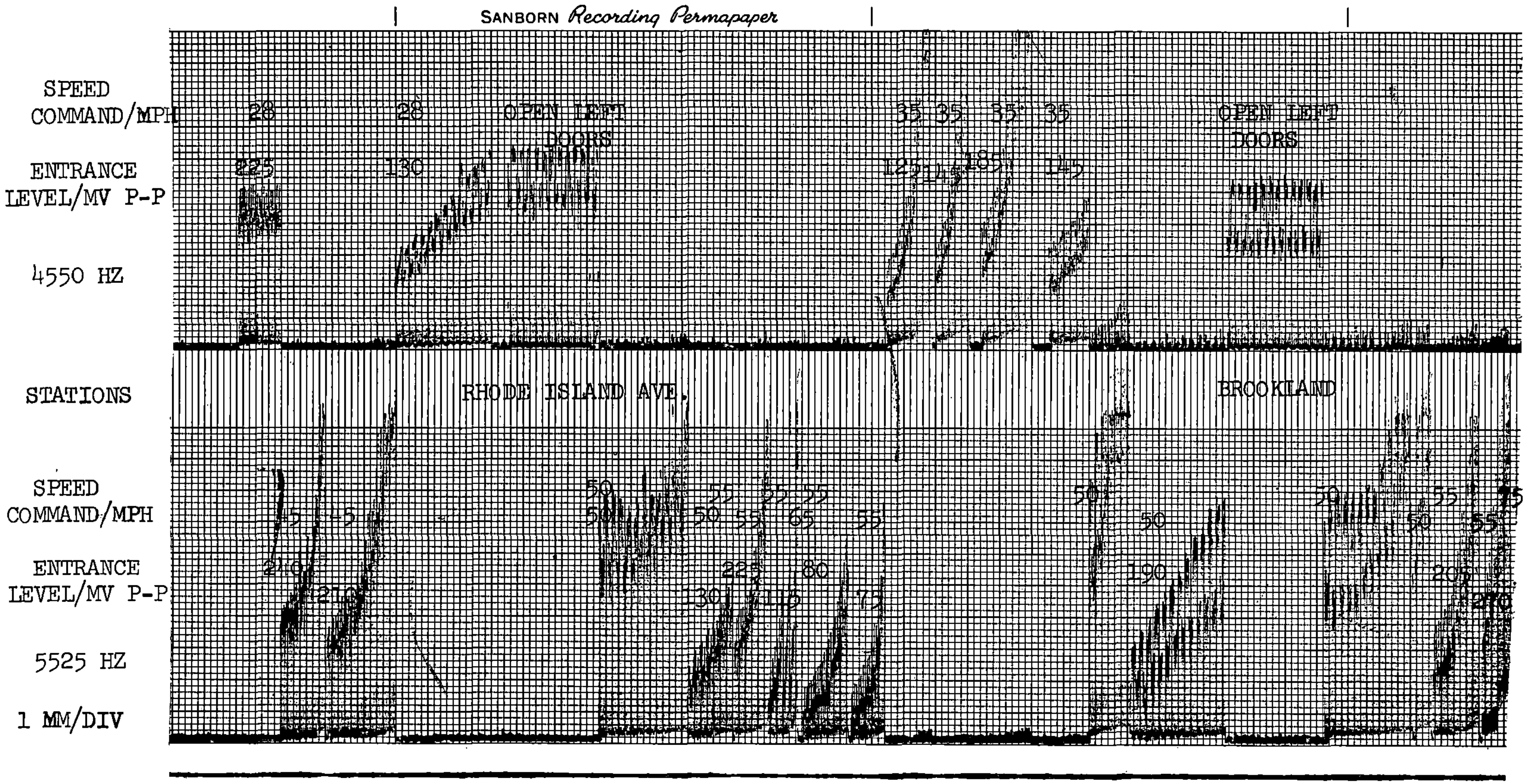
An assessment of the WMATA CBM has been conducted by members of the review team. Assessment procedures were developed in cooperation with WMATA personnel. Interface data were provided and discussed. Calibration measurements were made using a test setup in the WMATA electronics shop as well as on board a WMATA vehicle in the yard, using yard loops and a diagnostic test set. Recordings using a commercial audio cassette recorder and a WMATA CBM recorder were made in revenue service and on a test train in a simulated revenue run (i.e., automatic operation, program station stop, dwell, but no door opening at stations). The tapes and CBM playback unit were brought to the Transportation Systems Center (TSC) for subsequent analysis.

At TSC, the audio cassette recordings and CBM loop cartridges were stripped and subjected to preliminary processing. The analog channel and digital multiplexed channel were analyzed separately. However, since the CBM recorder is a continuous loop with no time code information, the analog channel which records wayside information was used for synchronization (i.e., vehicle location on the guideway).

Utilizing techniques developed during the TSC MBTA Red Line Automatic Train Control (ATC) Assessemnt, the CBM analog channel was stripcharted and analyzed. The output was annotated with physical location on the line (i.e., station location), wayside command values (speed, door, etc.), signal threshold levels, and timing (Figure 5-1). These data were compared with parallel recordings made at the DST receptacle using a TSC audio cassette recorder.

Two procedures are used to strip CBM digital data. CBM data recorded on the continuous loop cartridges were played back using the CBM playback unit due to the unique characteristics of the loop cartridge. The CBM data are also available at the DST receptacle in the cab and were recorded on a conventional audio cassette. The CBM data are identical to that recorded on the loop cartridge. The CBM digital data were demultiplexed and reformatted on digital tape.

MAY 10 1978
WMATA - RED LINE
DUPONT CIRCLE - SILVER SPRING



DIRECTION OF TRAVEL
1 MM/SEC

FIGURE 5-1. CBM ANALOG ATP CHANNEL STRIPCHART OUTPUT

Using these procedures, the recordings of the simulated WMATA revenue run were stripped and put on digital tape. Preliminary software was written to generate line printer output of the data frames. At the present time three preliminary printed output formats exist (Figure 5-2). The first two formats together contain all data bits in the frame. An attempt was made to group the data in a meaningful way for analysis subject to the physical constraints of the output media. The third format is a primitive stripcharting capability displaying power/braking transitions as a test application.

The review team made a CBM loop cartridge recording and audio cassette recording at the DST receptable during revenue operation over the entire WMATA system (i.e., Red and Blue Lines). Due to burnt-out distribution amplifiers and unplugged CBM recorders, only the CBM digital data channel was recorded at the DST on an audio cassette. These data have been processed, output presented in the three prototype formats, and provided to WMATA. Since the analog ATP CBM channel could not be monitored due to a later-found equipment failure, a mapping of the wayside/carborne ATC interface for the entire system could not be provided as intended.

Recommendations

1) A modification program should be initiated immediately to address the CBM interfacing problem. The modification is simple and straightforward requiring minimum manpower and parts (i.e., a few resistors in the trainline circuitry). This fix, together with the completion of the CBM hardware modification program, will result in a fully-operational CBM system.

2) The CBM should be further evaluated as a test/evaluation and diagnostic/maintenance tool to collect (with associated playback equipment), process, and display required information to support these activities. It should be noted that monitoring (using the CBM recorder or daily safety test receptable outputs) does not require separate test runs nor does it impact revenue operations. Specifically, it is recommended that the following application (problem) areas be addressed immediately:

```
OUTPUT.TAPE INTERPRETER                                                  DATE 16 NOV 1978    PAGE    0032
*****************************************************************************************************************
** RUN NO:    83  RECORDING DATE: 5/10/78  V.I.D. : 1266     RED LINE S.B.-YARD TO DUPONT/SILVER SPRING TO YARD.          **
** (RECORDED V.I.D.: 1264)                 DATA DIGITIZED ON MAG.-TAPE  8081                                           **
**                                                                                                                     **
*****************************************************************************************************************
** ASASASASAP TNTDTLAAAMACSTD K KMOPISSMOTSTBPIPDSSSCTPAGZZDC000CDRDRDLDLTDFRLTOTPRPRMOTSMFABFLMS  LMSML RRRRRP **  FRAME **
** CPTPTPTPTL RURSRNTUTAT/ARSAEBE/RSNKTAKYTRRSNLAKTSARBTOSSRLRRLLTCTOTCTOLOTTAE/EWSWST,WCSLTRSORP  PPGNN C1234/ **  COUNT **
** TDPDSDSDS  NMNTN CTCNPOP T Y YCK1IPOR PONT2IATPOTNN O R S LRRDL L L L 1OLLMSSSRERERLCO RPKB RC  GG GG      B **        **
**  : : :B: :  : : : O : :::: : : : T1PK:EP H TTA2PPCB: ::: :D::R1:2:3:4:3:::PT T1T2T . M : : :::  ::::: :::::: **        **
**  : : : : :  : : : : : :::: : : : : : : : : : : : : : ::: ::::: : : : : ::: : : : : : : : : :::  ::::: :::::: **        **
** 13155900 000000 2 0 1 1100 0 1 1 0 0 0 C 0 0 0 0 0 0 011 01111 1 1 1 1 101 0 0 0 1 1 1 1 1 111  00001 011011 **   601  **
**                                                                                                             **        **
** 15155900 000000 2 0 1 1100 0 1 1 0 0 0 C 0 0 0 0 0 0 011 01111 1 1 1 1 101 0 0 0 1 1 1 1 0 111  00001 011011 **   602  **
**                                                                                                             **        **
** 15000900 000000 2 0 1 1100 0 1 1 0 0 0 C 0 0 0 0 0 0 011 01111 1 1 1 1 101 0 0 0 1 1 1 1 0 110  00001 011011 **   603  **
**                                                                                                             **        **
** 12155900 000000 2 0 1 1100 0 1 1 0 0 0 C 0 0 0 0 0 0 011 01111 1 1 1 1 101 0 0 0 1 1 1 1 1 110  00001 111111 **   604  **
**                                                                                                             **        **
** 10155900 000000 2 0 1 1100 0 1 1 0 0 0 C 0 0 0 0 0 0 011 01111 1 1 1 1 101 0 0 0 1 1 1 1 1 111  00001 000000 **   605  **
**                                                                                                             **        **
** 09155900 000000 2 0 1 1100 0 1 1 0 0 0 C 0 0 0 0 0 0 011 01111 1 1 1 1 101 0 0 0 1 1 1 1 1 111  00001 000000 **   606  **
**                                                                                                             **        **
** 08155900 000000 2 0 1 1100 0 1 1 0 0 0 C 0 0 0 0 0 0 011 01111 1 1 1 1 101 0 0 0 1 1 1 1 1 111  00001 000000 **   607  **
**                                                                                                             **        **
** 08155900 000000 2 0 1 1100 0 1 1 0 0 0 C 0 0 0 0 0 0 011 01111 1 1 1 1 101 0 0 0 1 1 1 1 1 111  00001 000000 **   608  **
**                                                                                                             **        **
** 08155900 000000 2 0 1 1100 0 1 1 0 0 0 C 0 0 0 0 0 0 011 01111 1 1 1 1 101 0 0 0 1 1 1 1 1 111  00001 000000 **   609  **
**                                                                                                             **        **
** 08155900 000000 2 0 1 1100 0 1 1 0 0 0 C 0 0 0 0 0 0 011 01111 1 1 1 1 101 0 0 0 1 1 1 1 1 111  00001 000000 **   610  **
**                                                                                                             **        **
** 10155900 000000 2 0 1 1100 0 1 1 0 0 0 C 0 0 0 0 0 0 011 01111 1 1 1 1 101 0 0 0 1 1 1 1 1 111  00001 000000 **   611  **
**                                                                                                             **        **
** 11155900 000000 2 0 1 1100 0 1 1 0 0 0 C 0 0 0 0 0 0 011 01111 1 1 1 1 101 0 0 0 1 1 1 1 1 110  00001 000010 **   612  **
**                                                                                                             **        **
** 13155900 000000 2 0 1 1100 0 1 1 0 0 0 C 0 0 0 0 0 0 011 01111 1 1 1 1 101 0 0 0 1 1 1 1 1 111  00001 011011 **   613  **
**                                                                                                             **        **
** 14155900 000000 2 0 1 1100 0 1 1 0 0 0 C 0 0 0 0 0 0 011 01111 1 1 1 1 101 0 0 0 1 1 1 1 1 111  00001 011011 **   614  **
**                                                                                                             **        **
** 13155900 000000 2 0 1 1100 0 1 1 0 0 0 C 0 0 0 0 0 0 011 01111 1 1 1 1 101 0 0 0 1 1 1 1 1 111  00001 011011 **   615  **
**                                                                                                             **        **
** 12155900 000000 2 0 1 1100 0 1 1 0 0 0 C 0 0 0 0 0 0 011 01111 1 1 1 1 101 0 0 0 1 1 1 1 1 111  00001 011011 **   616  **
**                                                                                                             **        **
** 11155900 000000 2 0 1 1100 0 1 1 0 0 0 C 0 0 0 0 0 0 011 01111 1 1 1 1 101 0 0 0 1 1 1 1 1 111  00001 000010 **   617  **
**                                                                                                             **        **
** 11155900 000000 2 0 1 1100 0 1 1 0 0 0 C 0 0 0 0 0 0 011 01111 1 1 1 1 101 0 0 0 1 1 1 1 1 111  00001 000010 **   618  **
**                                                                                                             **        **
** 10155900 000000 2 0 1 1100 0 1 1 0 0 0 C 0 0 0 0 0 0 011 01111 1 1 1 1 101 0 0 0 1 1 1 1 1 111  00001 000000 **   619  **
**                                                                                                             **        **
** 10155900 000000 2 0 1 1100 0 1 1 0 0 0 C 0 0 0 0 0 0 011 01111 1 1 1 1 101 0 0 0 1 1 1 1 1 111  00001 000000 **   620  **
**                                                                                                             **        **
*****************************************************************************************************************
```

FIGURE 5-2a. CBM DIGITAL CHANNEL OUTPUT (FORMAT 1)

```
OUTPUT-TAPE INTERPRETER                                                    DATE 16 NOV 1978     PAGE     0142
*****************************************************************************************************************
** RUN NO;    83  RECORDING DATE: 5/10/78  V.I.D. : 1266    RED LINE S.B.-YARD TO DUPONT/SILVER SPRING TO YARD.    **
** (RECORDED V.I.D.: 1264)                 DATA DIGITIZED ON MAG.-TAPE  8081    FIRST FRAME ON THIS PAGE IS...  6C1  **
**                                                                                                               **
*****************************************************************************************************************
                                                            1111111111111111111111111111111111111111111222222222222222222222222222233333344
1111222244555555555566666666666777777777888888899999999990000011111122222333355555555556677777777222222334444445555446666777566778834
678901238901234567890123456789023456789012345601234567845678056789567890234012345678890123456745678_914501236789670123267858901455 8
-----------------------------------------------------------------------------------------------------------------------------------
00001010101111100000000000000010010000000000000000000000000010000000000000000001001100010000000000000110111101011111011111111011111111111
00001001001001000000000000000001100000000000000000000000000010000000000000000001001100010000000000010011111111011111011111111011111111111
00001001001001000000000000000001100000000000000000000000000010000000000000000000100010001000000000010111111111111111011111111011111111111
00001010001001000000000000000001100000000000000000000000000010000000000000000000100010001000000000010011111111101111101111111101111111111
100010010000000000000000001000010000000000000000000000000000100000000000000000001000100010000000000000011111101011111000011111011101111111
0000101011111111110000000000100010000000000000000000000000001000000000000000000100000001000000000000001101110101111100001111101110111111
1000100111111111110000000000100010000000000000000000000000001000000000000000000100000001000000000000001101110101111100001111101110111111
0000101011111111110000000000100010000000000000000000000000001000000000000000000100000001000000000000001101110101111100001111101110111111
0000101011111111110000000000100010000000000000000000000000001000000000000000000101010001000000000000001101110101111100001111101110111111
0000100111111111110000000000100010000000000000000000000000001000000000000000000100010001000000000000001101110101111100001111101110111111
0000101011111111110000000000100010000000000000000000000000001000000000000000000100110001000000000000001101110101111100001111101110111111
0000101011111111110000000000100010000000000000000000000000001000000000000000000101010001000000000000000101110101111100001111101111111111
1000100110111110000000000000001001000000000000000000000000001000000000000000000100010001000000000000000101110101111101111111101111111111
0000100100100100000000000000000110000000000000000000000000001000000000000000000100010001000000000000001111111101111101111111101111111111
1000100100100100000000000000000110000000000000000000000000001000000000000000000100000001000000000000001111111101111101111111101111111111
0000101000100100000000000000001010000000000000000000000000001000000000000000000100000001000000000000001111111101111101111111101111111111
1000100110111110000000000000001001000000000000000000000000001000000000000000000100000001000000000000001101110101111101111111101111111111
0000101010111110000000000000001001000000000000000000000000001000000000000000000101010001000000000000001101110101111101111111101111111111
0000101110111110000000000000001001000000000000000000000000001000000000000000000100010001000000000000001101110101111101101111101110111111
1000100111111111110000000000100010000000000000000000000000001000000000000000000100110001000000000000001101110101111100001111101110111111
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```

FIGURE 5-2b. CBM DIGITAL CHANNEL OUTPUT (FORMAT 2)

OUTBITS DATE 22 NOV 1978 PAGE 0017

** RUN NO: 83 RECORDING DATE: 5/10/78 V.I.D. : 1266 RED LINE S.B.-YARD TO DUPONT/SILVER SPRING TO YARD. **
** (RECORDED V.I.D.: 1264) DATA DIGITIZED ON MAG.-TAPE 8081 **

FRAME COUNT	ACT SPD	ATP SPD	P4	P3	P2	P1	S4	S3	S2	S1	SW2	SW1	CB/BK	B1	B2	B3	B4	B5	PL3	PL2	PL1	E1	E2
601	13	15											**							**			
602	15	15											**	**									
603	15	00											**	**									
604	12	15											**	**									
605	10	15											**				**						
606	09	15								**									**				
607	08	15								**									**				
608	08	15								**									**				
609	08	15								**									**				
610	08	15								**									**				
611	10	15								**									**				
612	11	15								**									**				
613	13	15											**							**			
614	14	15											**	**									
615	13	15											**	**									
616	12	15											**	**									
617	11	15											**							**			
618	11	15											**							**			
619	10	15											**							**			
620	10	15								**									**				
621	10	15								**									**				
622	11	15											**							**			
623	12	15											**							**			
624	12	15											**	**									
625	12	75											**	**									
626	11	75		**															**				
627	11	75		**															**				
628	11	75		**															**				
629	11	75		**															**				
630	11	75		**															**				
631	12	75		**															**				
632	15	75		**															**				
633	17	75	**																**				
634	20	75	**																**				
635	23	75	**																**				
636	26	75	**																**				
637	29	75	**																**				
638	31	75	**																**				
639	34	75	**																**				
0	37	75	**																**				

FIGURE 5-2c. CBM DIGITAL CHANNEL OUTPUT (FORMAT 3)

- B-1 friction brake application frequency (brake pad and disc wear problem)
- ATC/propulsion and braking interface (cycling)
- ATC wayside/carborne interface alignment and calibration
- Program station stopping malfunctions.

Lessons Learned

Since the CBM system is not presently fully operational at WMATA, only its potential can be assessed at the present time. Based on TSC preliminary processing of the CBM data and discussions with WMATA design and maintenance engineering personnel, the CBM concept has the potential to be a promising tool, useful in both the development and operational phases of a transit system. Although differing hardware implementations and capabilities may be appropriate for other transit properties based on their unique requirements and economic constraints, the concept is sound and addresses an important generic problem area which exists throughout the industry. Development and utilization of the CBM at WMATA during the coming months will provide the industry with the opportunity to evaluate the concept in the environment of an operating transit property and to establish its cost-effectiveness.

Tradeoff considerations should be made when designing a system between initial costs of providing diagnostic tools/equipment vs. estimated additional costs of maintaining equipment without diagnostic equipment. Experience in WMATA's case indicates that a diagnostic tool such as the CBM was planned for the system, but never utilized.

5.3.8 Leaking Brake Control Valve

Background

There are two brake control valve (BCV) assemblies located underneath each car: one for the forward truck and the other for the rear truck. These complex units consist of three basic sections:

1. Electronic brake controls, including a load-weight circuit
2. Electrically-actuated hydraulic brake servo valves
3. Nitrogen gas for pressurization of the brake fluid.

The design of the BCV is overly complex (FB). Many modifications by Abex, the supplier, have reduced the BCV failure rate to about 3/week. Problems range from hydraulic fluid leakage (porous pistons and leaking gaskets) to nitrogen leaks and electronic failures.

The BCV problems are most frequent when the seasons change (spring and fall), since changes in weather alter the pressure (temperature) settings in these devices (EV).

Status

Although the supplier has made many modifications and reduced the degree of failures to a great extent, the brake control valves are still failing due to the leakage of nitrogen gas or the leakage of hydraulic fluid through porous pistons or faulty gaskets. These failures require unscheduled maintenance and reduce car availability.

WMATA has discussed the problem many times with Rohr, the car builder, and Abex. Abex proposed to WMATA that they test a modified version of the original valve. Several modified valves were installed but were removed after a short period of time due to problems within these new valves.

Recommendation

Investigate use of simpler design for valve.

Lessons Learned

The more complex a system is, the tighter the requirements should be for the proper environmental testing of a piece of equipment prior to installation on a vehicle. In the case of the brake control valve as used in this operation, which has electronic circuitry, hydraulic brake fluid, and nitrogen gas incorporated into its housing, an extremely stringent quality control practice is mandatory to ensure reliability of this unit. The car specification did not require environmental testing of the brake system prior to installation on the car, nor did it require stringent quality control procedures for this vital system.

6. ASSESSMENT OF THE ATC SUBSYSTEM

6.1 INTRODUCTION

Overview

In any rail system, a mechanism must be established for controlling the movements of trains in order to maintain safety and operational efficiency. The methods by which this mechanism is implemented have been evolving ever since rail traffic began. The rate of evolution has accelerated in the last few decades as the capabilities of electronics have been applied to the problem. The result has been a trend toward higher levels of automation.

Within the spectrum of rail systems, rapid transit has a set of characteristics that influence the use of automation. The characteristics include high-speed operation, close headways, and human passengers. These characteristics lead to two important requirements for the train control system: it must be very reliable (i.e., fail infrequently) and, when it fails, it must fail safely.

The WMATA Metrorail system contains a high level of automation in its train control system. It is therefore important to understand how the basic design concepts of its Automatic Train Control (ATC) system were conceived, how they have been implemented, and how they have succeeded.

Basic Automatic Train Control (ATC) Design Concepts — In fulfillment of the decision made early in the planning process, the WMATA train control system is designed to primarily operate in a mode that is nearly fully automatic. Not all of the features of the system design are fully operational and effective at present. This description, however, explains the system as it was designed, and as it is expected to ultimately operate. The functions of starting, stopping, speed regulation, collision avoidance, route interlocking, dispatching, etc. are entirely automatic. An exception is the turnback operation at the end of lines.

The domain of an ATC system is typically subdivided into three areas. These are: Automatic Train Protection (ATP)-- including the safe separation of trains (collision avoidance), overspeed protection, and route interlocking; Automatic Train Operation (ATO) -- speed regulation, programmed station stopping, door opening and closing(vitally interlocked to ATP subsystem), and train starting; Automatic Train Supervision (ATS) -- establishes train routes, dispatches trains, tracks all trains, regulates traffic to maintain desired headways, monitors and controls traction power, monitors and controls station support facilities, and provides a display and command capability for central operators to supervise the above functions.

The WMATA ATC system is capable of executing the ATP functions in a fully automatic manner. ATO functions are designed to be normally executed automatically under the surveillance of an onboard operator. The ATS functions are designed to be carried out by a central computer, either automatically or with central operator assistance.

The WMATA ATO system is also designed to cope with failures in certain areas of the ATC system. For example, the system is capable of continuing to operate without the central ATS system. Scheduling and dispatching of trains would continue to be performed by operations personnel using local controls that are distributed throughout the system. Service quality would likely be degraded during rush hours or with close headways, but the trains would continue to run.

The effects of failures in certain aspects of the ATO subsystem can be overcome by reverting to manual control of individual trains. Sufficient signals are available to the operator to allow safe manual operation at full speed, if the ATP system is functional. In this combination of nearly fully automatic capability, with the provision for fall-back to nearly fully manual operation, the WMATA design is unique in contrast to most systems in this country.

Detailed ATC Operational Concepts - In a geographical sense, the "active" components of the ATC are located in three areas: onboard the vehicle (carborne); distributed throughout the system (wayside); and localized in the single centralized train control area (central). These areas are interconnected by two communications systems. The wayside/vehicle communication is concerned with the flow of signals (other than voice communication) between wayside equipment and the individual trains. Included in this area is the Train-to-Wayside Communication (TWC) subsystem used for ATS purposes. The data transmission system (DTS) interconnects central control and the distributed wayside equipment.

Functionally, the execution of the ATS, ATO, and ATP tasks are related to the geographical divisions of the system as depicted in Figure 6-1. These are described below.

1) Signaling Between Train and Wayside - Reliable communication of signals conveying commands and other information between wayside and trains is obviously an important part of an ATC system. In the WMATA system, several methods of exchanging signals are employed for various purposes.

The track circuit plays a number of signaling roles in the ATC system. A typical track circuit is shown in Figure 6-2. Except at switches, the running rails are laid without insulated joints. Blocks (individual track circuits) are created by the use of shunts. These shunts are selectively tuned to the various signaling frequencies that are used in the system. The shunts are used to introduce the signaling frequency currents into the running rails, to extract voltages created by the flow of the current, and to restrict the flow of the various currents so as to create a block system.

The signaling currents are used for several functions:

a) Train Detection (ATP) - In each block, a particular frequency is dedicated to train detection. As shown in Figure 6-2, the shunting action of the axles prevents the signal current from reaching the receiver. The absence of current is interpreted as an occupancy in that block.

b) Speed Command Transmission (ATP) - When a train is detected in a block, a second signal is generated that transmits, via the track circuit, a speed command to the train in the block. The command is encoded by a combination of modulation rate and carrier frequency.

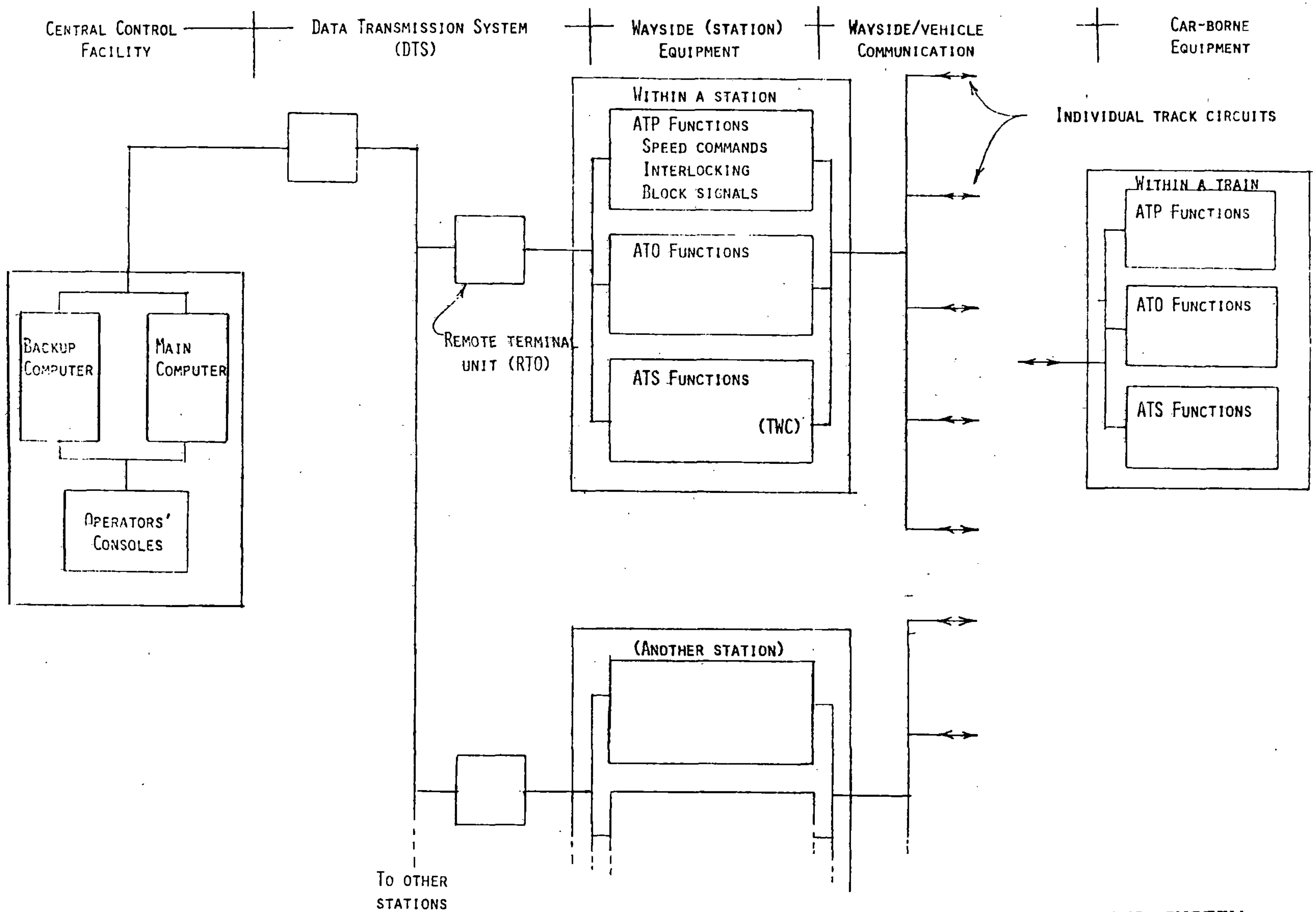

FIGURE 6-1. DISTRIBUTION OF ATC FUNCTIONS THROUGHOUT THE WMATA METRORAIL SYSTEM

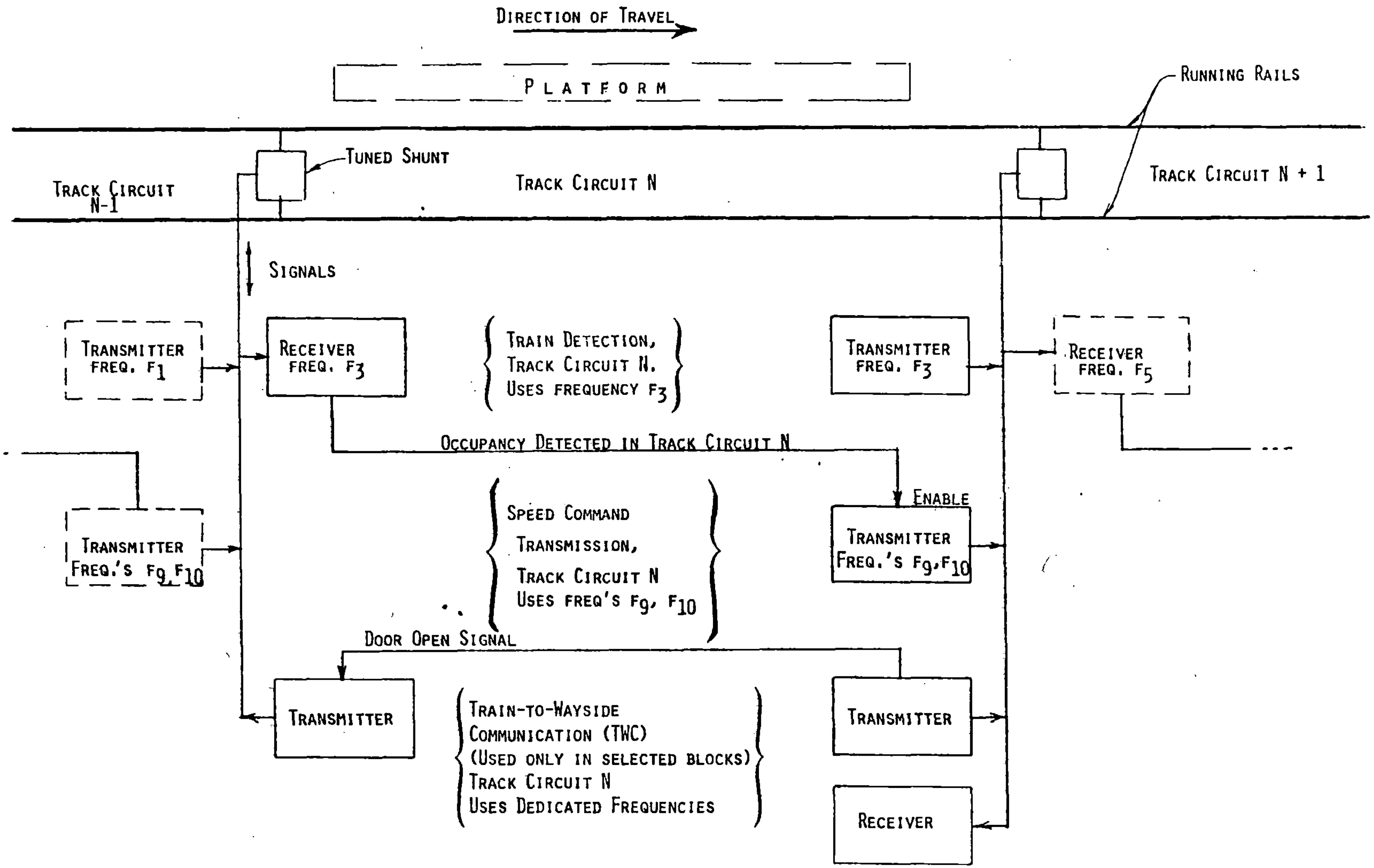

FIGURE 6-2. USES OF TRACK CIRCUITS FOR COMMUNICATION WITH TRAINS. BOUNDARIES OF TRACK CIRCUITS ARE DETERMINED BY THE TUNED SHUNTS. TWC COMPONENTS LOCATED ONLY IN CERTAIN TRACK CIRCUITS SUCH AS THOSE AT STATION PLATFORMS AND IN ADVANCE OF DIVERGING ROUTES.

c) Supervisory Messages (ATS) - Certain blocks within the system -- e.g., at station platform and at interlockings--are utilized to transmit information of a supervisory nature to the trains. This includes an ATS speed limit and a power limit command. These are initiated by the ATS system, and are the means by which the ATS system can modify the way the train responds to ATP speed limits. In response, the train replies with certain information, including train number, destination, length, and certain status information.

It should be noted that most all active electronic equipment associated with the wayside position of the signaling link is in protected locations in each station's train control room--i.e., mostly passive electronic components are distributed along the tracks. This has important consequences for maintenance, mean-time-to-restore (MTTR) and reliability under various weather conditions.

Another form of signaling between tracks and trains is used for executing programmed station stops at platforms. The objective is to automatically stop the trains with sufficient accuracy of location so that all doors of the train are aligned with the station platform. As a train approaches a station, it passes over three or four sets of trackside markers that provide position and grade references relative to the station and approach track. This information is used by carborne equipment to regulate the stopping profile. Most trackside markers are composed of passive electronic components. Active components involved in the detection and interpretation of marker signals are carborne.

2) Carborne and Wayside Equipment - Information passed via the wayside/vehicle communication subsystems is utilized by carborne and wayside equipment in implementing the various ATP, ATO, and ATS functions. The equipment that executes the vital functions is largely implemented with traditional vital relays. Solid-state electronics are employed for the ATO and ATS subsystem.

3) Central System - The central system includes a pair of general purpose computers. One is used as the primary controlling computer and the other is a backup. The computers are programmed to perform the basic ATS monitoring and controlling functions. Communication with the remote terminal units at the stations is via the data transmission system. Communication with the central operators is by means of CRT displays and control panels.

These display and control facilities are the means by which the central control operators monitor and interact with the system. System status is displayed on eight CRTs. Information displayed includes train identification, train location, interlocking schematics, electrification status, auxiliary systems status, and alarm indications. Central control operator commands are entered on functional and alphanumeric pushbuttons. These control facilities allow the operators to interact with the system by the selection of preprogrammed strategies and to manually operate remote control of electrification and support facilities equipment.

4) Data Transmission System (DTS) - This subsystem provides the communication facilities between the central computer complex and the Remote Terminal Units (RTUs) located at each of the stations. The DTS is a commercial communications system. All the points in the system are monitored continuously by the RTUs. New control commands are transmitted via the system to the station RTU as the interface to the end device.

The DTS is terminated at each station with Remote Terminal Units (RTUs). The RTUs interface to track circuits, interlockings, train-wayside communication, dispatch machines, electrifications and passenger station support systems, train ready indications, and fire alarms. The RTUs are scanned by central once per second. New commands are also output to the control points at each station every scan cycle.

Significant Features in ATC Design - The design of the WMATA ATC system includes the following features that should be noted:

1) Carborne Monitor - Each married pair of cars contains a carborne monitor system together with a continuous-loop magnetic tape recorder. The object is to continuously monitor and record the performance of all active vehicle subsystems on each car of each train. This system has the potential to be a powerful aid in diagnosing the source of ATC malfunctions.

2) Man/Machine Interface at Central Control - The centralized ATS system has excellent monitoring capabilities. The central operators can see the position of any and all cars on the revenue rails down to the block level on their graphics consoles. The central system was deemed to be sufficiently automatic so that a single central operating position was felt to be adequate.

3) System Log - The ATS system has a logging provision that permits it to record all state changes in the system every second. This feature has proven to be an excellent facility for debugging the ATC system. The detailed log shows all system commands and responses including train movements, so it can be used to analyze overall system performance; no other rapid transit system has the capability of centrally logging system changes with the resolution exhibited by WMATA.

4) Speed Code Generation - Speed codes are transmitted within a given track circuit only if a train is detected within that circuit. (Lack of received speed is interpreted by the train as a command to stop.) Among other things,

this represents a form of self-annunciation of a train detection failure. It also has a tendency to reduce the problems of cross-talk from nearby track circuits that could be transmitting on the same frequency. This feature, while not unique to Metrorail, is still noteworthy.

5) Detailed Design Approach - In general, the electronics equipment has been designed to achieve required performance using components with ordinary tolerance levels. Concerted attempts have been made also to utilize existing hardware of proven design whenever possible, and to minimize the amount of specialized or custom-designed gear.

6) Central Computer not Essential for Operation - A design concept is that the Central Train Control system is not essential for the safe movement of trains or for the basic system operation. Because some of the most sophisticated and difficult aspects of fully automatic control (and hence, most vulnerable) are focused in the central system, this design concept is important. This feature, also not unique to Metrorail, is also noteworthy.

7) Maintenance Facilities - To make a system maintainable requires, among other crucial contributions, a complete hierarchy of test equipment and procedures geared to the types of service and maintenance to be encountered. Primary and secondary maintenance of central, wayside, and vehicle equipment must be integrated. A fault which becomes apparent due to operational failure at a system level must be traceable from system to subsystem to module, and finally to the failed component. It is not simple to write procedures for troubleshooting which generally point the maintenance technician in the right direction, but this must be made a goal of the original contract. When a system fails an operational test, but there is no clear direction as to what components should be checked in what manner, the result may well be unreli-

able operation in the future resulting from wrong maintenance diagnosis in the present.

Early in the specification process the need was recognized for some items of specialized test equipment. These include equipment for a Daily Safety Test, a Vehicle Test, and a Dynamic Vehicle Test.

A Daily Safety Test setup is installed on all tracks where trains are stored. It performs a sequence of tests on the ATP system of the train. These include the response to each speed command, together with a check for underspeed and overspeed detection using a simulated tachometer input.

The dynamic vehicle tester is capable of a more complete exercise of the ATC system and other carborne equipment. It is located in the repair shops.

The repair shops also have a computer-based test stand for ATC systems that have been dismounted from cars for dynamic vehicle testing. The wayside training room is a setup of 50 feet of track, train control track circuits, a switch and signal, and a complete set of station and wayside control electronics.

8) Manual Control Option - One of the ATC positive design features is the degree to which manual operation is provided for in the event of a failure in the automatic circuitry. This has not always been the case for new automated transit systems. This provision for manual backup is one of the primary reasons why the overall performance of the transit system has been as dependable as it is, even though the hardware reliability of some of the ATC subsystems has been low. The carborne ATP system has four basic operating modes. These are:

   a. Automatic - All starting, stopping, and speed regulalation is controlled by the electronic circuitry.

b. Manual with ATP - All starting, stopping, and speed regulation is controlled by the train operator as long as the vehicle is decoding proper speed codes. The train is allowed to travel at speeds up to those being displayed to the train operator. The train operator is protected from overspeed by the onboard ATP. This allows train movement with a minimum delay when the vehicle ATO speed regulation circuitry is defective.

c. Manual with ATP/Stop and Proceed - All starting, stopping and speed regulation is controlled by the train operator up to a maximum speed of 15 mph as long as no speed codes are displayed or decoded. The train must first come to a complete stop before it can enter into this mode. The mode is used in the yard, or whenever speed codes are not being received by the vehicle.

d. Manual with ATP Cutout - All stopping, starting, and speed regulation is controlled by the train operator. No overspeed protection is offered. Metrorail's present operating rules require that the ATP cutout switch be safety wired, and the wire to be broken only after central control's approval.

The ATC door control circuitry has three modes of operation. They are:

1) Automatic Mode - All door opening and closing is done automatically by the vehicle ATP equipment upon a command from the station ATP circuitry. The doors will not open unless the train is at zero speed, the train is properly berthed in the station platform, and brakes are applied. The station equipment selects the side of the train that is to have the doors opened. Door closure will begin when the station ATP equipment indicates that the dwell is complete.

2) Automatic-Manual-Mode - Door opening is under control of the ATP circuitry as in Automatic mode; door closing is under the control of the train operator, as a function of passenger demand.

3) Manual Mode - All door opening and closure is controlled by the train operator in this mode.

The train operator has the capability to cancel a programmed stop and override automatic door control.

Five modes of operation are available in terms of route selection through interlockings. In all cases, a route is granted only if all other conditions indicate that it is safe to do so. They are:

1) Automatic Route Selection - Wayside circuitry responding to the train destination information transmitted by the train via TWC or block occupancy of an approaching train will set and lock a route, if it can be done safely.

2) Central Automatic Route Selection - For trains being dispatched according to schedule from a storage yard or in the case of certain failures of the wayside automatic selection equipment, the train control computer will set and lock a route for a train, if it can be done safely.

3) Wayside Route Selection - In case the wayside automatic selection equipment does not align a route or aligns the wrong route, the train operator can select the correct route manually from a wayside panel. The panel is located just in advance of the interlocking and is accessible from the vehicle cab window.

4) Central Manual Route Selection - The central control operator has full control over each interlocking which allows inhibiting automatic/wayside route selection and/or manual selection of any route within an interlocking.

5) <u>Local Manual Route Selection</u> - There is a local control panel in each train control room that houses the circuitry for each interlocking. Full control over the interlocking is available from this panel for maintenance or in case of central control failure.

For terminal areas, where it is necessary to reverse the direction of trains, the five modes of operation mentioned above allow the reversal to take place with complete safety. Normally this is an automatic function not requiring central intervention.

At the time that this report was being written, trains were normally operated in the Automatic ATP mode, with all starting, stopping, and speed regulation being performed by the ATC system. Some trains, however, were operated in the Manual with ATP mode. At the beginning of the study period, the control was normally under the Automatic-Manual modes with the circuitry controlling door opening and the train operator manually closing the doors. However, during the summer of 1978, as a result of two reported "wrong side" door openings, Metrorail's operating rules were changed to require full manual control of doors. Route selection and route reversal, were normally performed in Automatic mode at Silver Spring, Dupont Circle, and Stadium Armory stations. At National Airport all route selection, route reversals, and dispatch were performed manually from the local control panel in the train control room. Train movement was also performed in the Manual mode with ATP/stop and proceed.

6.2 CURRENT STATUS

As mentioned earlier, the WMATA ATC system was designed to be nearly fully automatic. Although efforts were made to employ proven technology as much as possible, inevitably new problems arose as this sophisticated system was put into operation. During the early stages of this study, a considerable amount of emphasis was placed upon identifying the key problem areas that WMATA faces. An overall assessment, however, is that while the reliability of some of the vehicle subsystems is low, the fundamental design concepts and the existing mechanisms for solving current problems are sound. At this point, there is no fundamental reason why the ATC system cannot eventually perform in a completely satisfactory manner. No key or fundamental problems were found. It is recognized, however, that route expansion, reduced headways, and future line merges will exacerbate some of the existing problems and create new ones. As a result, some functions of the ATC have not been fully implemented; others have failure rates that are higher than they should be.

The general impression of the review team is that:

1) the system operates well in terms of its short history;

2) the staff and vendor are aware of the significant problems and, in most cases, are pursuing solutions;

3) there is no reason to expect that the ATO and ATP subsystems will not fulfill their design expectations; and

4) there are a number of areas, particularly in the ATS system, where problems may arise as the Metrorail system expands.

6.2.1 Present Operating Characteristics

The WMATA train control (TC) contract specified quantitative levels for Equipment Reliability (MTBF), Repairability (MTTR), and Availability (MTBF/[MTBF+MTTR]) for each of the major vehicle and wayside TC subsystems. This is now common practice for all new transit systems. The first application of these measures in a transit procurement was for BART. Table 6-1 is a reproduction of one section of Part One of the WMATA contract.

During the time that this report was being written, most, if not all, of the wayside ATC equipment passed this acceptance criterion. Many of the subsystems were exceeding the specified MTBF levels by a factor of five or more.

TABLE 6-1. WMATA ATC SPECIFIED RELIABILITY LEVELS (Partial Listing)

Equipment	Availability (Min.)	MTBF (Min.)	MTTR (Max. hours)
AF Track Circuit			
Train Detection	0.99995	18,000	1
Speed Command Transmission	0.9999	12,000	1
Carborne APT except Door Control	0.99995	33,600	3

Vehicle ATC subsystems did not fair as well. A preliminary assessment conducted during October 1977 indicated that some of the vehicle subsystems were falling quite short of their specified reliability levels. The two biggest problem areas were program stop and vehicle ATP, both areas experiencing significant levels of hardware failures. Since October 1977 both General Railway Signaling (GRS) and the ATC system supplier, WMATA, have been modifying those vehicle subsystems. Preliminary indications are that those deficiencies are in the process of being corrected. During the study period, the reliability evaluation process was not complete.

In addition to the ATC reliability data, another source of data was made available -- the Operations Impact Reports. These are daily summary logs maintained by the central supervisor of the Transportation-Rail Department. A summary of that data for the three-week period April 17, 1978 through May 5, 1978 is presented in Table 6-2.

6.2.2 Achieved Level of Automation

For various reasons, certain automatic features designed into the WMATA ATC system are not yet fully operational. To that extent, the level of automation on the system is lower than the design level. Comments on these features follow:

TABLE 6-2. INCIDENTS AFFECTING REVENUE SERVICE

Period (days)	15
Car Miles (miles)	480,000
Total Incidents (number)*	314
Incidents Delaying Service (number)**	99
Incidents Charged to ATC (number)***	102
Incidents Delaying Service and charged to ATC (number)**	28
Incidents % ATC (%)	32
Delaying Incidents/Delaying ATC (%)	27

* All incidents affecting revenue (wayside failures, vehicle failures, vandalism, etc.)

** Causing a delay of 2 or more minutes to one or more trains.

*** Includes only those incidents diagnosed by the Transportation Rail Department as ATC-caused.

1) <u>Door Opening and Closing</u> – The system was designed to automatically stop trains (programmed stop) at predetermined locations along station platforms. When fully stopped, the doors on the cars are to open automatically and to close automatically after an interval determined by a preset dwell timer (unless, of course, the operator should manually hold doors open for passenger safety or convenience).

   At the time of the review leading to this report, train operators had been instructed to open and close the doors manually. This mode of operation resulted from two conditions. First, the program stop equipment was not deemed sufficiently reliable in stopping the train in an accurate location. Therefore, the operator was required to verify the location before opening doors; in some cases, the operator had to manually berth the train into the proper location. Secondly, the process of transmitting from wayside and interpreting on the train the open doors left/right commands was reported to have malfunctioned on at least two occasions. The operator was thus given the additional responsibility for opening doors on the correct side of the train.

The present impact on operations is minimal. Most passengers are unaware when manual moves are used to augment the automatic program stop equipment, unless the station is skipped because it has overshot the platform. (This is rare.)

The variations in station stopping and dwell times that result from manual moves will become significant when closer headway operation is attempted. It is possible, of course, that the technical problems may be overcome by that time.

2) Absence of Line Merges – Metrorail is not presently operating any lines that merge dynamically with any of its other lines. At present there is only one traditional (over/under) transfer station. WMATA's plans call for five such dynamic merges. In addition, headways (presently 5 minutes at peak times) are scheduled to be dropped to 3 minutes in the near future. Of course, the advantage of these merges is that they minimize the passengers' need to change trains. A potential disadvantage is that the entire system becomes much more sensitive to seemingly small local service perturbations. A local perturbation can delay a train; this can cause a local merge conflict which in turn impacts the more global interlaced route schedules. For example, two 6-minute headway lines that merge into one 3-minute headway line require that each train requests its route within ± 1 minute of the scheduled time of the merge (assuming 60 seconds to change and lock a route) if delays, or holds, are to be avoided. A potential concern is that normal variations in run times would, with dynamic merges, result in a degradation in service quality over the entire system. Variations in run times could result from such diverse causes as manual override of automatic

door closing, any vehicle component failure affecting train performance, manual train movement, etc.

WMATA plans to use a first-in/first-out algorithm for controlling merges. Such an algorithm uses information on train movements from a localized area of track. This restricts the ability of the central control system to maintain headways as compared to a global merging algorithm. Global algorithms in turn depend on the central computer's ability to continuously gather complete and accurate information on the global state of the system. This can be a disadvantage as it results in more and more of the ATS hardware and software components in the critical decision-making chain.

3) ATS Level of Automation – The system is being operated in a manual mode. The central computer is used to monitor train movements and central control dispatches trains manually. The automatic features, such as train dispatching and train scheduling, are not being involved because of turn-on problems in the data acquisition hardware and software, and the tracking algorithm.

6.2.3 Specific Observations

1) Maintenance Practices – Metrorail, its consultants, and suppliers have taken care to attempt to develop a system that is maintainable. During the study period, Metrorail personnel were performing all ATC primary maintenance. Most secondary maintenance (module, principally circuit board repair) was being performed by their supplier, GRS. Metrorail's plans call for more and more of this secondary maintenance function to be performed by Metrorail personnel. This represents a significant step which could cause problems if it is not well planned. The level of documentation supplied (drawings, circuit descriptions, test procedures, and diagnostic equipment) is designed to inform a maintenance technician when a

module is within specification and when it is not. The present level of documentation, test equipment, procedures, and training is generally not adequate for performing secondary maintenance. Additional facilities would be required to do this work.

2) No Trouble Found (NTF) – The October 1977 vehicle ATC reliability data indicated that approximately 30 percent of the reported ATC failures result in the maintenance technician not being able to reproduce or fix the problem. In addition, approximately 40 percent of those modules removed as defective from a vehicle result in secondary maintenance forces not being able to reproduce or repair the problem. Finding and correcting design flaws that result in intermittent problems is a time-consuming, costly, and often necessary process. Metrorail and GRS built in some diagnostic tools for monitoring the ATC subsystems (i.e., Carborne Monitor (CBM), the System Log tape (SYS Log), capability to monitor all blocks at central control, etc.).

   NTFs typically arise when the actual problem is intermittent, or was ascribed to the wrong piece of equipment by the original observer. (A vehicle operator may sometimes be unable to tell whether a problem is caused by onboard or wayside equipment.) There is no alternative but to return such equipment to service, where the problem may manifest itself again. Discussions with maintenance workers at the Brentwood Yard confirm the frequency of this class of problem.

   NTFs have an impact on operations, service and maintenance. Because the equipment is returned to service, a single intermittent problem can cause multiple service disruptions.

   Studies of maintenance procedures and modifications of certain subsystem components have been suggested as offering possible solutions. There is no ongoing systematic study of the problem, although the equipment supplier has been made aware of it and is considering possible causes. Further work on this problem is essential. It is recommended that the tools listed above be exploited in locating sources of NTFs. It is important that these tools be used and problems that result in NTF not be ignored.

3) Size of Effort in Equipment Design – It is significant to note that the entire staff of the Metrorail's Equipment Design Department is presently seven people. Two more are expected within the next year. This is not, however, a big department, though it is handling big tasks, such as the evolution of a specification for another purchase of transit vehicles, and the expansion of the railroad from 26 to 50 miles of track. It is unrealistic to suggest extensive projects to investigate the status of present equipment without suggesting department growth as well.

4) Central System Software – Software maintenance is a problem because WMATA staff have to work with inadequate and incomplete documentation. About 85 percent of the software is written in assembly language rather than a high-level language like FORTRAN, making it more difficult to learn and maintain.

   Some of the software, primarily the operating system software for the central computers, is proprietary. A listing for this software has not been delivered to WMATA. WMATA personnel, therefore, do not have the documentation needed to analyze and debug the system. This problem is aggravated by the fact that the operating system was tailored to WMATA's configuration and needs and is not supported by the computer system vendor. As the system becomes more heavily loaded, system bugs not yet visible could appear, impacting overall system performance. WMATA staff will not be in a position to correct these faults without this initial documentation.

6.3 KEY PROBLEM AREAS

Preceding sections have discussed the ATC hardware and its current performance. The present Metrorail mode of operation has also been discussed. This section discusses the impact of planned system expansion on service reliability. Line mileage is planned to change from 26 to 100. The number of dynamic merges is planned to change from 0 to 5, the peak number of trains from 24 to approximately 70, peak headway from 5 minutes to 2 minutes. This section describes some of the steps necessary before these goals can be achieved. Most concern is centered around the role and readiness of the central computer system. System expansion is likely to require greater and greater dependence on the central computer system. Single tracking around stalled trains, resolving route conflicts and dynamic schedule changes, are examples of some of the tasks that are likely to be needed.

There have been instances of computer system overloads at the current manual ATS operating levels. The WMATA staff has analyzed and corrected the overload situations. More are sure to occur as the system expands to incorporate more trains and tracks, and when the programs that perform traffic regulation are involved.

The known problems have been caused by several programs contending for the same memory. In general, the programs are assigned to run in fixed memory segments and once they are loaded they have to run to completion. This can, and has, resulted in conflicts with the asynchronous dynamic scheduling requirements imposed by external events.

In addition to the described core contention problems, disc contention problems may appear as the need for processing data increases with system expansion. Additional external system events caused by increased operator activity, more alarms, etc., will result in more frequent calls to load and execute programs. More data will have to be logged when the capability to gather and record train system operating statistics is introduced.

The WMATA staff has recognized the need to quantify computer system resource utilization under various operating loads. Their intent is to use this information to optimize their current memory allocation and program scheduling strategies, and to have the data to predict the computing load in the future, as the system expands.

There are currently no provisions for monitoring computer system performance. An outline is being developed with WMATA staff to monitor specific program activity and quantify a specific program utilization of computer resources.

1) The ATS system is designed with a single central control position. Only one operator at central control can control train movements. It was felt that this was sufficient in view of the level of automation that was designed into the system. This has already proven to be a deficiency when the central operator has to respond to problems at several points in the system at the same time. The requirements for central intervention will be more frequent as the system expands from its present 26 miles of double track to 100 miles of double track with merges. Major changes will be required to expand to two central control positions.

2) The only effective way to test software changes is to install them and run the railroad. The system simulator is limited; it cannot be used during revenue service since both computers are required to run the simulator; it only simulates the Red Line and does not simulate electrification and support facilities; it cannot be used to evaluate the overall effect of changes in program scheduling. The result is that it is very expensive and time-consuming to make and test program changes and program scheduling strategies.

3) The train tracking algorithm cannot cope with short blocks. It expects the train to advance no more than one block during a one-second scan cycle. If the train moves completely through a block between scan cycles, the algorithm gets confused; it leaves the known train in the last block where it was seen and it creates a new unknown train two blocks ahead.

   This confuses the scheduling algorithm, and central operator intervention is required. This is now being corrected by a program change.

   The DTS scans the station remote terminal units every second and updates its internal, system-state tables. The station terminal units and track-to-wayside communication systems operate on a 1.2-second scan cycle.

   The software that was delivered allowed for loss of data on up to one out of three scans. Occasional communication problems caused a loss of two out of three or more; this problem was also corrected by the contractor. Presently, only marginal equipment operation causes problems; spotting this marginal operation and also failures needs to be defined.

6.4 RECOMMENDATIONS AND LESSONS LEARNED

As a result of this study, it is recommended that:

1) WMATA examine the capabilities and readiness of the Central Train Control Computer System, particularly with respect to its ability to handle the fully-expanded Metrorail system.

2) WMATA continue to develop and use the diagnostic tools purchased such as the Carborne Monitor and the SYSLOG files, which represent unique opportunities to measure current system performance. Use of these tools would seem the best way to solve many of the existing hardware reliability problems.

3) WMATA consider increasing the level of effort presently assigned to the ATC section in Equipment Design. It is significant to note that the entire staff of the Metrorail Equipment Design Department at the time of this study was seven people. It is not a big department, considering the number and scope of tasks it is handling such as the evolution of a specification for another purchase of transit vehicles, the expansion of the system from 28 to 50 route miles, determining what subsystems should be accepted, designing and/or approving equipment modifications, and providing day-to-day maintenance and operational support.

4) WMATA also increase the available manpower presently being assigned to monitor and analyze ATC subsystem reliability data.

For new transit properties, it is recommended that:

1) New properties in conceptual design stages seriously consider Metrorail's provision for manual backup in the event of hardware failures. Metrorail's ATC manual backup capability is one of the primary reasons why the overall performance of the transit system has been as reliable as it is, even though the hardware reliability of some of the ATC subsystems has been low.

2) New properties in the planning stage hire their own train control staff prior to the conceptual design of the ATC system. The operations and maintenance viewpoint is easily neglected unless the Authority has developed its own staff.

3) New properties follow Metrorail's example in providing a substantial level of maintenance diagnostic test equipment. During the specification process it is extremely important to consider the real need for adequately detailed documentation and test equipment.

7. STATION SYSTEMS

7.1 TECHNICAL DESCRIPTION OF STATION SYSTEM EQUIPMENT

The two station subsystems found to be most troublesome during the assessment and which comprise the major dynamic elements of the station system are:

1) Automatic Fare Collection System (AFCS); and

2) Escalators.

7.1.1 AFCS Description

The AFCS used at WMATA was supplied by Cubic Western Data (CWD). Major elements of the system include the Farecard Vending Machines, Faregates, and a Data Acquisition and Display System (DADS). Magnetic encoded Farecards are purchased at selectable monetary values (i.e., \$.05 increments up to \$20.00) from vending machines in the station mezzanine area; payment plans also exist to purchase pre-encoded Farecards from the system. The AFCS supports the specification of complex fare structures as a function of origin-destination (O-D) pairs and time. The present WMATA fare structure is multizone and varies during on and off peak periods; it is complicated by the fact that the system extends into different government jurisdictions, with differing fare policies.

Farecards are processed by the Faregate on entry and exit from the revenue portion of the system. The Farecard uses a stored-value concept and is the Metro patron's key to the system. The Faregates are the means whereby Metro gradually collects the value stored in the Farecard; they allow passage into and out of the system, determine the value of the completed ride, and deduct that value from the patron's Farecard. Farecard Vendors deliver Farecards to patrons, either for cash or for cash plus the value of a used Farecard. The Addfare Machine allows a patron to add sufficient value to his Farecard to exit from the system should the remaining value of his card be less than the cost of his just-completed ride. In a second mode, the Addfare Machine will deliver \$1 worth of change for use in the Transfer Vendors and parking lot gates. The Data Acquisition and Display

System, which is located in each station kiosk, monitors AFC equipment status and operation; it also provides accounting data from each machine to be used in financial control and to aid in the detection of fraud or theft. In addition to these core elements, support functions are required. Money-handling equipment and facilities process and control all money and Farecards which are entered into or distributed by the AFCS. Parking lot equipment provides access control and fee collection for patronage of the parking areas which are a part of the Metro System.

Critical hardware elements of the system include the Farecard vending equipment (i.e., coins and bills) and the Farecard transport.

The Farecard Vendor

The purpose of this machine is to furnish Farecards of any chosen value (up to a settable limit) for cash or cash plus the trade-in value of a used card. The machine has a storage capacity for 3,000 Farecards.

The Vendors are identifiable from a distance by the characteristic color of the front panels, both of which are golden yellow. Also, these machines are found only in the free-area of a station. Closer approach allows the legend "FARECARDS" to be read in the upper panel, as well as allowing the symbol of the Farecard to be discerned. Just below the legend, a display of green letters informs patrons "CHANGE RETURNED" if the change hoppers in the machine have an adequte supply. Just above the center of the lower panel, the operating panel presents the information and controls required to use the machine for the purchase of Farecards. The flow of information and use is from left to right, as though reading a book.

The first instruction, identified by a large "1," is the phrase "INSERT MONEY." Just below the legend is a sub-panel containing the bill insert bezel, with symbols of one- and five-dollar bills showing the proper orientation for insertion, and a coin-input slot with symbols showing acceptable coins (nickels, dimes, quarters, and halves). As money is inserted, a numeric display in the center sub-panel keeps track of the sum. Just below the value displays are two rocker switches, one labelled with a dollar sign and one labelled with a cents sign; both switches are labelled with pluses at the top and minuses at the bottom. Using these switches, the patron can select any desired initial value of Farecard (as long as it does not exceed the value of cash plus remaining value on a traded-in Farecard). The legend at the top of this sub-panel illuminates upon the insertion of money; this legend is "2 FARECARD VALUE." At the same time the "2" illuminates, the legend at the right-hand sub-panel also illuminates, "3 FARECARD." Included in this subpanel is a large illuminated push-button which announces "PUSH FOR FARECARD." Immediately to the right of the push-button is the delivery slot for the new Farecard. Just below this subpanel is the input slot, with an instruction legend, for insertion of a used Farecard which has remaining value.

At the top of the operating panel is a series of latent displays which are illuminated as appropriate. They include "OUT OF SERVICE," "SEE ATTENDANT," "$20 MAXIMUM," "BONUS INCLUDED," "TRANSACTION CANCELLED - MONEY RETURNED," "OUT OF CHANGE - USE EXACT MONEY," and "TAKE FARECARD." The internal logic of the machine illuminates each legend as needed.

Also located on the money insert subpanel are two small push-buttons, one a bent coin release and the other for a "CANCEL" decision.

Below the money insert subpanel is a money return cup. All money inserted in the machine is held in escrow pending either card issue or cancellation of the transaction. When the card is issued, money from the escrow is deposited in a bill magazine and/or a coin collection container; if the transaction is cancelled, either by the patron after a change of mind or by the machine because the patron inserted too much money, the contents of the escrow sections are returned in the money cup.

Should there be a difference between the amount of money inserted and the selected value of the Farecard, this difference is also returned to the patron in the form of change. To supply this change, there are two quarter hoppers and one nickel hopper in the machine. There is a maximum difference of $4.95 returnable in change.

The legend "$20 MAXIMUM" listed previously applies only to the amount of inserted cash; this value is a settable function and may be changed if experience indicates the wisdom of such a change.

As mentioned previously, any inserted money is deposited in a bill magazine or a coin collection container. Although of different shapes, these units have similar functional characteristics. Both are locked into the machine, and both have entrance passages which lock upon removal from the machine. Release of these locks to remove the contents is possible only after certain security measures are taken, in order to protect the revenue until it is inside the secure revenue facility.

Faregates

The Faregates are the transition point between the free and the paid areas of the stations. They also read, encode, and verify information on the Farecard; in addition (in the case of an exit gate) the remaining value is printed on the card so the patron can have a record. The Faregate consoles are 72 inches long, 11 inches wide, and 38 inches high. Operational speed permits the passage of 27 passengers per minute through each aisle.

There are five variations of the gates in order to accommodate the requirements of differing station layouts: reversible; entry; exit; end (A); and end (B). A reversible gate contains both entry and exit card transports and two barrier leaves as well as aisle-control logic. An entry gate contains only an entry transport and one barrier leaf. An exit gate contains only an exit transport and one barrier leaf as well as aisle-control logic. An A-type end gate contains only a single barrier leaf. A B-type end gate contains only a single barrier leaf and aisle-control logic.

Upon entry, the Farecard is checked for at least minimum value, proper codes, and sufficient remaining print space. If acceptable in all these factors, the barriers are opened and the patron is given access to the paid area. During this passage through the transport, the station and time of entry are encoded, read, and verified.

Upon exit, the time of entry is checked to be certain a preset limit of time-in-the-system is not exceeded, codes are checked for validity, and the station of entry is read to determine the fare due. The fare is subtracted from the stored value in the card; the remaining value is coded into the card and printed on the next available line in human-readable form. Again, the processes of encoding, reading, and verifying are carried out. Should the card's value be reduced to zero by the fare just collected, the card is not returned to the patron.

In either entry or exit, latent displays are illuminated at the proper time to inform patrons of the proper procedures.

Upon approach to the gate array, the proper direction of passenger flow is indicated by an arrow on a green circle. Aisles which are controlled for the opposite direction display a red circle with a white central bar and the words "WRONG WAY." These messages appear on the ends of the consoles.

In addition to the direction indications on the ends of the consoles, other messages are presented on the tops. At an entry transport, messages include "GET NEW FARECARD" and "STOP SEE ATTENDANT." At an exit transport, the messages are "GO TO ADDFARE," "STOP SEE ATTENDANT," and "EXACT FARE FARECARD NOT RETURNED."

7.1.2 Escalator Description

The current WMATA system makes extensive use of escalators. Most, if not all, of the 11 Red Line and 18 Blue Line stations have escalators; many do not have any stairways as backup, but rely completely on the escalators (plus the elevators required for the elderly and handicapped).

All of the escalators are of the same type: the Westinghouse modular unit design. These escalators are made up of 20-foot-long building blocks or modules. There are 279 such modules in the system for a total of over a mile of escalators. There are at least three escalators at each station where they are used, and many of the larger stations have four escalators. Assuming an average of 3.5 escalators at each of the 29 stations (or roughly 100 escalators), the average escalator length is roughly 55-feet or 2-3/4-modules long. The longest escalators are at DuPont Circle and Rossyln stations and are 9-modules (180-feet) long at both locations.

The escalators are all maintained by Westinghouse Escalator Sys-ems, located in Upper Malboro, Maryland, under a maintenance contract with WMATA. The modular design simplifies installation of the units.

A metal cover plate flush with the floor must be removed at the top or base of an escalator to gain access to the drive system for maintenance or repair.

The controls for each escalator for on/off, forward/reverse, and speed are even more inaccessible on most units; the operator must be prone on the ground and extend his arm forward above his head to reach the control switches.

7.2 CURRENT STATUS

7.2.1 AFCS

At the system level, AFCS problems result in inhibited passenger flow/throughput upon entry/egress at stations. At the present time, a major AFC product improvement program is currently underway by CWD in cooperation with WMATA. It is difficult to assess the impact of this program on total system performance without a failure reporting system which includes AFCS money handling equipment and "soft" failures (c.f. Section 7.3.1, Recommendations). However, preliminary indications are positive and passenger perception of the AFCS performance is improving.

7.2.2 Escalators

All of the WMATA escalators are serviced by Westinghouse under a maintenance contract. The quality of service has been high, and the availability of escalators has always exceeded the contractual requirement of 98 percent.

It is estimated from Westinghouse data that the mean-time-between-failures (MTBF) is about 700 hours. This suggests that a large, responsive Westinghouse maintenance effort is required to keep the escalators running with a high availability. (There is no contractual requirement on MTBF in the present maintenance contract.)

About 14 service calls are received daily for the escalators. Of these about half are valid or "chargeable" calls; the other half are not necessary since the unit is already operational before Westinghouse service personnel arrive at the scene.

The number of escalator failures that keep an escalator out of service for eight hours or longer is estimated to be only one to two per month.

7.3 KEY PROBLEM AREAS

7.3.1 AFCS

Background

There is a very positive AFC product improvement program currently underway by CWD in cooperation with WMATA. Specific problem areas addressed by the program include money handling equipment, fare card transport, and software. These problems result in money jams/rejects, fare card jams/rejects, equipment-out-of-service conditions (vendors and gates), and obstructed passenger flow as a result of queuing at gates.

There has been an extensive evaluation of AFC hardware and system operation by both WMATA and CWD. There are a number of modifications installed which are being evaluated at this time. For example, the bill validation and coin acceptor equipment has been exhibiting low reliability. Transactions per unit between failures for the bill validator is approximately 8,000 in this transit application compared to 20,000 in traditional commercial applications. This money handling equipment is provided by a commercial vendor and is the same as that found in vending machine and bill changing machine applications. CWD has made some modifications (c.f., heating element to bill validator) and has upgraded factory acceptance test procedures. CWD is evaluating extensive modifications to the existing bill validator and has initiated their own bill validator development program. CWD has also redesigned the Farecard transport and has made a number of software changes including recycling the transport in the Faregate to clear card jams. It is difficult to definitively assess the impact of these modifications on AFC system performance without an improved failure reporting system (c.f. Section 7.3.1, Recommendations).

Recommendations

It is recommended that a comprehensive R and M data reporting process be developed which includes money-handling equipment and those "soft" failures handled by the kiosk attendant (e.g., fare card jams, money-handling equipment jams, etc.) in order to accurately characterize AFC system performance and aid in tracking the product improvement program. This data is not currently captured by the CWD maintenance reporting process and reliability program. This type of comprehensive reporting is required to close the gap between passenger perception of AFC operation and the results of a quantitative reliability program.

Lessons Learned

Data collected and analyzed as part of the improved comprehensive R & M data reporting process (coupled with the results of the product improvement program) would prove very useful to properties considering AFC and to UMTA in assessing AFC hardware and system operation in a transit environment. Such data would identify and support any R & D requirements in the AFC area.

Use of commercial money-handling equipment for transit application should be minimized until reliability of such equipment is improved and/or proven in a transit environment.

7.3.2 Escalators

Background

The key problem areas can be divided into two categories: short-term problems and long-term problems. The short-term problems are the excessive service calls due to vandalism; the long-term problems are the excessive service calls due to mechanical failures in parts such as handrail drive units, handrails, or combfingers. The impact of an escalator failure is often not too great, since there are always at least three escalators (sometimes four) at each station where used. Also, until repair work is started, the disabled escalator can serve as an extra stairway.

Vandalism and misuse account for most of the minor or short-term breakdowns. The most common form of vandalism is for a rider to kick the skirt plates at a particular location above a concealed microswitch. The resulting vibration will throw the microswitch and cause the escalators to stop. It must then be restarted by a mechanic, who turns on the inconveniently-located reset controls. The delay in waiting for a service mechanic to arrive can be typically 10 to 30 minutes, depending on remoteness of the station to the disabled unit.

Excessive failures in the mechanical drive units, the handrails and the combfingers have led to long-term breakdowns where the units are down for days instead of hours while waiting for parts. Many of these failures, such as cracked shafts in the main drive, are primarily due to the fact that this is a new Westinghouse design, and all the design defects have not been removed as yet by appropriate modifications and retrofits.

Recommendations

1) It is recommended that the restart controls be more conveniently located so that the station attendant can restart the unit for a vandalism type of a stoppage.

2) It is recommended that WMATA not take over the maintenance of these escalators until sufficient design improvements and retrofits have been implemented to achieve a MTBF consistent with conventional, nonmodular escalator designs.

Lessons Learned

1) Locate escalator controls in more accessible locations for easier restart in case of vandalism initiated stoppages.

2) Require that the escalator vendor demonstrate the required MTBF from actual service data before ordering escalators of a particular design. This will keep the escalator maintenance costs at a reasonable level in revenue service.

3) Alternate means of access/egress to platform areas such as stairways should be provided to handle passenger traffic when escalators are nonoperative and/or for emergency reasons.

8. ASSESSMENT OF POWER DISTRIBUTION SUBSYSTEM

8.1 TECHNICAL DESCRIPTION

The WMATA electric-power system consists of the following parts:

- AC service rooms, which supply power to the passenger stations and the non-traction power to the tunnels.
- DC traction rectifier stations, which rectify utility power and supply the nominal 750 Vdc power to the power rail.
- Substations and service rooms for the WMATA shop, office, and other facilities.
- Electric utility feeders, which supply power to the ac service rooms, the dc traction rectifier stations, and the other WMATA shop, office, and other facilities.

The focus of attention during this assessment was on the first two items, primarily the AC service rooms.

At the present time, there are 73 ac service rooms and 27 dc traction rectifier stations in service. Of the ac service rooms, 15 are above ground and 58 below ground. Of the traction rectifier stations, 13 are above ground and 14 below ground.

8.1.1 AC Service Rooms

Each ac service room is supplied by one electric utility feeder (e.g., 13.8 kV from Potomac Electric Power Co. (PEPCO)) which feeds power at 480 V to one half of the passenger station and one half of the tunnel to the next passenger station. The electrical equipment includes a primary circuit breaker, dry-type transformer, drawout-type 480-V secondary bus and tie breakers, molded-case 480-V feeder breakers, Uninterruptible Power Supply (UPS), batteries, and other auxiliary equipment. The service rooms for the underground and above ground stations are located at platform level. The ac service rooms supply power for lights, escalators, elevators, air conditioning (ventilation), pumps, fare collection, electronic facilities in the passenger stations, and lights in the tunnels. Two ac service rooms are provided for each below ground passenger station, with provision of one room supplying the essential load of the other room during shutdown of all or part of the equipment of one room. Only one ac service room is provided for each above ground passenger station. It is electrically equivalent to the two service rooms at the ends of each underground passenger station. Therefore, double failure must occur in a service room before passengers are affected, but still without the impairment of train operations.

8.1.2 DC Traction Rectifier Station

Each dc traction rectifier station is supplied with two electric utility feeders and, in turn, feeds 750 Vdc power to the traction power rails. The equipment includes primary ac and main dc breakers, rectifier transformers and rectifier units, and other auxiliary equipment. The stations are located underground in the downtown area, and above ground elsewhere, but generally between passenger stations.

The dc traction rectifier stations supply traction power to the power rails at each location for both directions of train operation. Each station consists of a minimum of two transformers and rectifier assemblies, two electric utility ac feeders, multiple dc feeder cables to the power rails, and the required circuit breakers and controls. Furthermore, all of the output feeders of the dc traction rectifier stations are effectively paralleled to the common power rails. Consequently, a failure of part or all of a rectifier station will not impact on passenger operations.

8.2 CURRENT STATUS

The 58 ac service rooms that are located underground have experienced several troublesome maintenance and reliability problems, while the dc traction rectifier stations, and the equipments contained therein, have been relatively free of trouble.

The least reliable equipment in the underground ac service rooms have been the Uninterruptible Power Supplies (UPS), which have experienced a large number of failed units in service.

8.3 KEY PROBLEM AREAS

8.3.1 Introduction

The key problem areas for the underground ac service rooms are:

- excessively dirty ventilation,
- high failure rates and high maintenance efforts experienced for UPS equipment, and
- ground fault protection insufficiently selective.

These key problems are discussed separately below, even though they are obviously related.

8.3.2 Excessively Dirty Air

Background

Air used for ventilation of the underground ac service rooms is drawn from the adjacent subway tunnel at the end of a passenger station. This ventilation air is then returned to the same tunnel. The tunnel air is laden with high concentrations of small iron and carbon particles (10 microns or less) which are given off by the brake pads, power rail contactor shoes, wheels, and rails as each train applies its brakes when approaching a station stop. It is not surprising that fairly high levels of iron and carbon dust are also present in the ac service rooms adjacent to these tunnels, despite the use of one-stage, roller-type air filters in the incoming air ducts to the service rooms.

These one-stage filters are not efficient enough to properly cleanse the tunnel air; also, when they become clogged due to inadequate maintenance, the reduction in differential pressure in the room permits the passing trains to force tunnel air directly in through the exit louvers.

The iron and carbon particles in this air penetrate the electronics equipment operating in these rooms, causing electrical short circuits and premature failures and breakdowns of solid-state electronics, especially in the UPS units. This can cause partial blackouts of stations and tunnels and increased equipment maintenance.

WMATA is well aware of the problem, and has initiated a program to wash down the tunnel walls to reduce concentrations of iron and carbon particles. Also, WMATA is providing more attention to the maintenance and upkeep of the present roller-type filters.

Recommendations

The review team has studied the problem and proposes three recommendations:

1) Switch from tunnel air to outside air for ac service room ventilation,
2) Switch to a more efficient (finer) roller material for the filters, and/or
3) Add fixed second-stage filters in series with the present roller-type filters.

Lessons Learned

The lessons learned for ventilating the ac service rooms are:

1) Use of clean ventilating air in the underground ac service rooms will greatly reduce maintenance requirements for the equipment operating therein.
2) Plan to use outside ambient air rather than tunnel air to ventilate underground ac service rooms. This is not difficult to do if it is planned for in the original design.
3) Plan to use 2-stage filters to assure adequate cleaning of the incoming air for the ac service rooms. A 2-stage design would reduce the particle or dust concentrations by at least an order of magnitude.
4) Plan to use a deep, dish-shaped filter, rather than a flat one, for the second stage of the air intake filter. This would reduce maintenance and also reduce the pressure drop across the filter.

8.3.3 UPS Equipment

Background

The 86 UPS units installed in the ac service rooms provide power for tunnel lighting and station lighting, as well as the passenger entry and exit monitoring equipment. If one UPS is not functioning, the station lighting intensity is lower (since every alternate light is off) and the tunnel to the next station is in complete darkness for half the distance to that next station.

The UPS equipment has required a high WMATA maintenance effort for several reasons:

- A high failure rate, basically caused by excessive iron and carbon-rich dust in the ac service room air (as previously mentioned) shorting out electronic components.
- A non-uniformity of the types and designs of the UPS units in service has complicated maintenance efforts, requiring greater maintenance training and a greater inventory stocking of spare parts. Six manufacturers have installed approximately 25 different UPS designs in the ac service rooms, which is due to bidding and construction procedures and lack of a standardized design specification for WMATA.

WMATA has increased its maintenance training for the UPS equipment and has installed air filters on some UPS units. These filters are not effective, since the UPS cabinets are not sealed units, and some dirty air by passes the filters and enters the cabinet through cracks and seams.

Recommendations

1) When more UPS units are procured for the future WMATA stations, standardize the UPS design to one specification, and perhaps two or three sizes to simplify maintenance, maintenance training, and the stocking of spare parts.
2) Coat the circuit boards in the current units with epoxy to minimize the effects of iron and carbon dust.

3) Completely seal the cabinets, rather than attempt to add filters.
4) Further increase the number of trained technicians to service the UPS equipment.
5) For future buys, modularize the UPS into more than one cabinet and provide maintenance switches to turn off power on each module for safer servicing of the units. This approach will also provide greater operating flexibility during repairs. For example, it would then be possible to perform repairs on the rectifier (charger module) while supplying a power output from the inverter module.
6) Investigate the use of an ac service room battery or emergency light packs to provide emergency lighting in the event of a UPS failure.

Lessons Learned

The lessons learned for UPS equipment in transit systems are:

1) Set up a uniform design specification with only two or three sizes (of the same design) for the entire transit system before procurement is begun. This will simplify maintenance, maintenance training, and the stocking of spare parts.
2) Isolate the circuit boards from dust by means of epoxy coatings or the use of sealed cabinets.
3) Modularize the design into two or more cabinets to provide more flexible operation and a safer maintenance environment.
4) Provide a sufficient number of maintenance switches to control power in the area requiring maintenance for reasons of personnel safety and flexibility.

8.3.4 Ground Fault Protection

Background

Ground fault protection is built into each of the 1200 A main secondary breakers located in each of the ac service rooms.

However, there is no provision for ground fault protection in either the feeder panel main breakers (bus breakers) rated at 400 A or the molded case breakers used for each of the branch circuits downstream from the 400 A bus lines. With this present arrangement, a ground fault at any point in a branch circuit will cause the main secondary breaker feeding it to trip out, removing all non-essential power from that half of the passenger station (The essential load will still be carried by the UPS.) This will mean loss of escalator power, some station lighting, etc. until a maintenance worker can locate the cause of the fault and isolate it so that the main secondary breaker will remain closed when reset.

There are typically 20 to 30 ground faults per year in the WMATA system. Many of them occur during escalator maintenance and repairs. These ground faults result in highly visible passenger inconvenience.

WMATA is aware of the problem and the solution; they have requested that any new ac service rooms include ground fault protection. Also, they have begun to gather data for incorporating or adding ground fault protection to the existing branch circuits.

Review Team Action/Findings

The review team has investigated, in some detail, the feasibility of adding to or replacing the present molded case breakers for the branch circuits. Eleven manufacturers were contacted, and it was found that no manufacturer makes breakers with Ground Fault Current Interruption (GFCI) that are physically interchangeable with the present panel-mounted breakers. However, for the WMATA applications, Westinghouse and/or Federal Pacific breakers could be mounted separately near the present panels for each of those branch circuits where the ground faults have occured most frequently.

Recommendations

The review team recommends that this latter approach be taken to upgrade the current equipment. In addition, it is recommended that a GFCI capability be specified in all branch circuit breakers in the ac service rooms being specified for the expanded transit system.

Lessons Learned

The lessons learned in the area of ground fault protection for the non-traction power that is distributed by the ac service rooms are:

1) Ground fault protection is a good method for protecting electrical equipment, since the current settings can be set lower than the damaging fault currents.
2) Passenger inconvenience, increased maintenance, and damage to other equipment should be minimized whenever a ground fault occurs. The way to minimize damage to other equipment is to provide ground fault protection (WMATA provides this). The way to minimize both passenger inconvenience and added maintenance after a ground fault occurs is to limit the zone that is tripped out, so less equipment is down and the cause of the fault is more easily determined. Both goals can be achieved by use of additional ground fault protection in the circuit breakers for each branch circuit. This is most easily accomplished when it is planned for in the initial electrical power distribution system design.

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