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This report will be of interest to railcar maintenance professionals concerned with improving railcar maintenance fault-diagnostic capabilities through the use of artificial intelligence (AI) technologies. It documents the results of a demonstration of an AI-based program that acts as a "diagnostic assistant" for transit railcar propulsion systems. The diagnostic program uses a hybrid AI approach with both model-based reasoning and expert system rules. The AI tool was tested at the Washington Metropolitan Area Transit Authority (WMATA) on direct current chopper propulsion systems of the 3000 series railcars. The system was determined to be easy to use and effective in diagnosing propulsion system faults.

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TRANSIT COOPERATIVE RESEARCH PROGRAM

Report 44

Demonstration of Artificial Intelligence Technology for Transit Railcar Diagnostics

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TRANSIT COOPERATIVE RESEARCH PROGRAM

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

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

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

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

Because research cannot have the desired impact if products fail to reach the intended audience, special emphasis is placed on disseminating TCRP results to the intended end users of the research: transit agencies, service providers, and suppliers. TRB provides a series of research reports, syntheses of transit practice, and other supporting material developed by TCRP research. APTA will arrange for workshops, training aids, field visits, and other activities to ensure that results are implemented by urban and rural transit industry practitioners.

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

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

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

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

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FOREWORD

By Staff
Transportation Research Board

TCRP Report 44, "Demonstration of Artificial Intelligence Technology for Transit Railcar Diagnostics," will be of interest to railcar maintenance professionals concerned with improving railcar maintenance fault-diagnostic capabilities through the use of artificial intelligence (AI) technologies. The report documents the results of a demonstration of an AI-based program that acts as a "diagnostic assistant" for transit railcar propulsion systems. The diagnostic program uses a hybrid AI approach with both model-based reasoning and expert system rules. The AI tool was tested at the Washington Metropolitan Area Transit Authority (WMATA) on direct current chopper propulsion systems of the 3000 series railcars. The system was determined to be easy to use and effective in diagnosing propulsion system faults.

The results of TCRP Project E-2, "Artificial Intelligence for Transit Railcar Diagnostics," were published as *TCRP Report 1* in 1994. The objectives of this project were to assess the potential application of artificial intelligence (AI) techniques in diagnostic practices in the railcar maintenance environment and, where appropriate, to recommend steps to introduce such practices. The researchers (1) identified AI techniques that are applicable to the diagnosis or prediction of railcar failures; (2) identified the AI techniques with high probabilities of success; (3) estimated the magnitude of potential benefits from using these techniques; (4) identified, in order of priority, the railcar subsystems (e.g., propulsion, brakes, doors) that benefit most from application of each of these techniques; and (5) developed a research program for systematically evaluating and implementing these techniques.

The final report for this project recommends that a follow-up demonstration of AI technology be considered. The report recommends that a demonstration of the technology focusing on the railcar propulsion system be performed to evaluate its benefit to the diagnostic process. The report concludes that the use of AI technology in diagnosing railcar propulsion system problems could pay for itself in 1 year if it could provide a 7.2 percent reduction in the propulsion system mean time to repair.

Under TCRP Project E-2A, research was undertaken by ANSTEC, Inc. to develop and demonstrate a "diagnostic assistant" computer program using AI technology to provide efficient and effective support for diagnosing transit railcar propulsion system problems.

To achieve the project objectives, the researchers (1) selected a demonstration site based on established criteria; (2) specified and procured an AI software shell and workstation hardware; (3) developed functional and causal models of the propulsion system and generated diagnostic rules for input into the AI software; (4) pre-tested the AI system, with debugging as necessary; (5) tested the AI system in actual field operation at three WMATA facilities; and (6) evaluated the AI system diagnostic capability.

CONTENTS

COOPERATIVE RESEARCH PROGRAMS STAFF

PROJECT PANEL E-02A

AUTHOR ACKNOWLEDGMENTS

The research reported herein was performed under TCRP Project E-2A by ANSTEC, Inc. Mr. Ian Mulholland, Program Manager for Advanced Technology, was the principal investigator. Mr. Zoran Kahric was the Knowledge Engineer and Mr. E. G. "Jerry" Willey, Vice President, provided management oversight.

The Washington Metropolitan Area Transit Authority (WMATA), Washington, D.C., provided substantial support for this effort. We would like to thank all of the individuals who participated in the program development. In particular, we would like to thank Mr. Mike Lohman, Mechanic A Electrical, for his diagnostic expertise and his assistance during testing. We would also like to thank Mr. Lemuel Proctor, General Superintendent, Railcar Maintenance, for his support.

EXECUTIVE SUMMARY

OVERVIEW AND APPROACH

This report presents the approach, process and findings to the development of an advanced technology computer program designed to provide diagnostic assistance to transit railcar maintenance technicians. The Transit Cooperative Research Program Project E-2A is a demonstration intended to show the feasibility of an artificial intelligence (AI)-based program performing diagnosis of a railcar propulsion system.

The "diagnostic assistant" program is based upon a hybrid AI approach combining model-based reasoning (MBR) and expert system rules. Using MBR techniques allows diagnosis of complex systems, even if there are no current diagnostic expertise or if the system changes. Expert rules, on the other hand, allow for the addition of expertise that has been developed over years of experience by senior maintenance technicians.

This effort was accomplished through eight main tasks:

- Field Test Site Selection,
- Evaluation of Current Maintenance Facility Systems,
- Hardware and Software Acquisition
- Data Collection and Knowledge Engineering of Railcar Propulsion Subsystem,
- Establishment of a Diagnostic Baseline,
- Human-Computer Interface Prototype,
- Training and Demonstration, and
- Operational Test and Evaluation.

FINDINGS

It was decided at the beginning of the project that the railcar system targeted for diagnosis should be the direct current (DC) chopper driven propulsion system. This technology is no longer in production, but there are still a large number of DC chopper railcars in use. Cost of maintenance of the propulsion systems of these cars is high. Nine transit agencies that maintain DC chopper cars were approached about participating in this effort. The Washington Metropolitan Area Transit Authority (WMATA) was selected as the site to perform the field test.

WMATA's current maintenance facilities were reviewed in order to identify sources of data and knowledge that could be used to develop the propulsion system model and diagnostic rules. Reference manuals, test equipment, documentation, and the WMATA maintenance database, Maintenance and Reliability System (MARS), were used, along with interviews of maintenance technicians. The knowledge engineering processes developed seven models encompassing the entire railcar propulsion system. Rules were developed from the propulsion system experts. Initial probabilities were used to label each component as good or bad and these were developed through the MARS database in consultation with the experts. It was hoped that a quantifiable propulsion system diagnostic baseline could be developed. That baseline (time and accuracy of diagnosis) could then be compared against the AI program. Unfortunately, the historical data on propulsion maintenance did not allow the development of the baseline.

A commercial off-the-shelf AI shell was purchased for the diagnostic program. The program was developed on a desktop system and run on three laptops, all personal computer compatible. The human-computer interface was driven mainly by the AI shell software with some customization possible. Maintenance technicians were trained on the program and asked to test the system against actual propulsion faults. The documentation of the tests were evaluated including program critique sheets.

CONCLUSIONS AND RECOMMENDED APPLICATIONS

The development and testing of the artificial intelligence (AI) diagnostic program resulted in several conclusions. The conclusions are listed below in descending order of importance.

1. The AI diagnostic program approach is feasible.
2. There appears to be the potential for cost savings in railcar maintenance using this approach.
3. The AI diagnostic program is effective in performing diagnosis and is easy to use.

4. The diagnostic program allows workload leveling.
5. Developing the diagnostic program provides valuable insight into the diagnostic process.
6. The diagnostic program can be effectively used to train technicians in diagnosis.
7. Development of the diagnostic program is fairly quick and easy.
8. There are some faults that are difficult to diagnose.
9. There is some resistance to using to the program to perform diagnosis.

This effort has shown that development and use of an AI-based "diagnostic assistant" program is feasible. Development of the program is straightforward and does not require a substantial capital investment. Correct diagnosis can be determined in an efficient manner even by maintenance technicians who do not have extensive experience in diagnosing propulsion system faults.

The use of the "diagnostic assistant" program by a transit agency should save maintenance dollars, as well as increase railcar availability. Quantification of the cost savings potential could not be accomplished in this demonstration effort. Determination of cost savings would require tracking of the total maintenance time for propulsion system faults across an extended use of the "diagnostic assistant" in operational mode (ensuring that the program was used).

Most maintenance technicians who use the program find the "diagnostic assistant" convenient and effective. This program provides personnel who are less experienced the ability to perform needed propulsion system diagnosis. The effect of this is workload leveling related to that diagnosis. Propulsion system diagnostic expertise is now available to all shifts. Additionally, diagnostic expertise is maintained in the program even when expert maintenance personnel leave or retire.

Working with maintenance technicians and managers in the knowledge engineering process allows insight into the diagnostic process. The rigors of the process provide the transit agency visibility into the current maintenance activities in a structured environment. The diagnostic program also provides a valuable training tool for maintenance personnel.

The program is fairly easy to develop. The development and modification of the propulsion system model was accomplished in short time. The entire project, including the time required for developing this report, was completed in 18 months. The majority of labor was expended by the Program Manager and the Knowledge Engineer. The cost of the hardware and software for the development platform and one run-time platform was approximately $30,000.00.

There are some propulsion system problems that could not be solved. They fall into two categories: (1) Intermittent faults, and (2) Faults for which a test could not be performed. There are maintenance personnel who are resistant to using this advanced technology. Those who are already experts in performing diagnostics do not need to use the program. Others may be reluctant due to concern about job security or their lack of computer skills.

The effort described in this report was the initial application of the "diagnostic assistant" program and was intended as a proof of concept demonstration. The recommendations are listed below in descending order.

1. Collect cost data for one year.
2. Interface the diagnostic program into the maintenance information network.
3. Use component-based maintenance reporting.
4. Expand the diagnostic program to include additional railcar systems.
5. Add event logging to railcars to capture anomalous data.
6. Add multimedia and on-line technical reference to the diagnostic program.
7. Use diagnostic program as training aid.
8. Integrate diagnostic program and on-line reference material into new railcar designs.
9. Research adapting diagnostic program as an on-board monitor.

The "diagnostic assistant" program is capable of being operationally deployed to diagnose WMATA railcar propulsion system faults. Use of the program for a year would provide the necessary data to determine cost savings as well as increased availability data for the railcars. The transit industry could use the development cost information versus the cost savings data to justify using this approach at other transit authorities.

Interfacing the diagnostic program with the maintenance information network can develop additional capability. Additionally, the transit industry should use component-based maintenance reporting. This will allow tracking maintenance by various parameters such as detailed fault information, waiting time (before maintenance commences), time to diagnose, and type and time of repair. The diagnostic program should be expanded to include other transit railcar systems. The automatic train control system and the braking system are the recommended additional systems to be included into the "diagnostic assistant" program. It is also recommended that an on-board event-logging capability be implemented for those railcars that do not already have such.

The addition of multimedia capability to the program will help the technicians. On-line technical manuals, historical maintenance data, graphics, pictures and even video clips can be used to great effect by the technicians. The "diagnostic assistant" program can also be used to train maintenance personnel in diagnosing propulsion systems. Additionally, procurement specifications for new railcar design could benefit from integrated diagnostic capability and on-line technical reference material. The diagnostic program could ultimately be placed on board the railcar and used to monitor the status and condition of the railcar. It is recommended that research into this capability be performed.

CHAPTER I

INTRODUCTION AND DEMONSTRATION APPROACH

INTRODUCTION

PROBLEM STATEMENT

Transit railcar failures create major problems for transit agencies. Annual cost of diagnosis and repair is substantial and can run into millions of dollars for many transit agencies (Muotoh, 1984)[1]. Availability of transit railcars is also impacted by failure thereby decreasing revenue and increasing capital costs. Reducing the time that the railcars are out of service can help alleviate these problems. One way to reduce railcar downtime is to improve maintenance diagnostic capability.

Maintenance personnel perform a range of tasks across many railcar subsystems. The technicians have varying levels of expertise and those that are considered experts in diagnostics are considered critical to quick railcar repair. Unfortunately, there are often not enough experts to support the total needs of the transit agencies. Additionally, as the experts retire, their expertise is lost. In cases where that expertise was associated with older technology railcars the loss is very difficult to replace.

The use of advanced technologies provides the potential of reducing these problems. *TCRP Report 1*, "Artificial Intelligence for Transit Railcar Diagnostics," recommended the use of artificial intelligence (AI) technology in the form of a "diagnostic assistant" computer program for maintenance personnel. The program can help reduce the time and cost, and increase the accuracy of failure diagnosis. The report also stated that the "diagnostic assistant" program could be used to preserve institutional expertise, train novice maintenance personnel, and provide workload leveling.

TCRP Report 1 recommended initial application of the "diagnostic assistant" program for transit railcar propulsion systems. It was reported that many transit maintenance managers believed that increasing the diagnostic capability on the propulsion system would reduce overall maintenance costs. Additionally, the complexity of the propulsion system encompassing electrical, mechanical, and electronic components would provide a good showcase for the "diagnostic assistant."

OBJECTIVE

The objective of this report is to provide transit authorities with the results of the development and demonstration of a "diagnostic assistant" computer program developed under TCRP Project E-2A. The focus of this effort was on demonstrating the approach of using AI technology and mobile computing hardware to provide efficient and effective support for diagnosing transit railcar propulsion systems.

ORGANIZATION OF REPORT

The rest of Chapter I describes a notional approach to how the railcar maintenance technician would use the "diagnostic assistant" program, a discussion of the AI technologies deployed in the program, and a short description of the tasks performed in this effort. Chapter II reports the results of the development and demonstration of the "diagnostic assistant" program. Chapter III discusses the conclusions of the development and demonstration of the "diagnostic assistant", as well as recommendations for additional applications of this approach.

Appendix A provides a characterization of the series 3000 railcar propulsion system. Appendix B illustrates the seven models developed for the use in the "diagnostic assistant" program. Appendix C lists the set of rules associated with each of the seven models. The two appendices, B and C, taken together, constitute the knowledge base developed for the program. Appendix D is a glossary of terms.

[1] Muotoh, D., and Elms, C., Cost Savings Potential from Improvement in Railcar Reliability and Maintainability, UMTA-IT-06-0273-81-1, April 1984, USDOT.

DIAGNOSTIC PROCEDURE

The use of the "diagnostic assistant" is intended to help the maintenance technician perform diagnosis of the propulsion system quickly and accurately. In most cases the program will be especially useful to those technicians who have not already developed extensive expertise in propulsion diagnosis.

When a transit railcar has reported a propulsion system problem, the maintenance technician will begin diagnosing the problem using the "diagnostic assistant" loaded on a laptop computer. The use of a laptop allows the technician to go where the railcar is, even if that is in the field.

The maintenance technician will enter symptom data into the program, which will then suggest the next best test to be performed. The test is selected based upon how much information it will provide to diagnosing the problem as well as the cost of the test. The cost was defined when the program was developed and may be in terms of dollars, time, or difficulty. The technician enters a value of good or bad for the test based upon a parameter list provided by the program. The program will temporarily change the probabilities of each component being good or bad. The program will again suggest the next best test. This process will continue until the faulty component is found. When the diagnosis is finished, the program will permanently change the probabilities for the components and thereby become more efficient.

DEMONSTRATION TECHNOLOGY

TCRP Report 1 recommended using a hybrid AI approach for the demonstration program. Two AI techniques, model-based reasoning (MBR) and expert systems, were used together. A hybrid approach allowed the strengths of each AI technique to be used.

The model-based reasoning technique uses models of the system being diagnosed along with an understanding of how those models function. The models are composed of boxes linked together with input and output paths. Depending upon the specific MBR approach taken, the boxes may represent physical components of the system, functional components of the system, or casual factors of the system. The input and output paths may represent physical or electrical connections, functional connections, or causal probabilities. Additionally, in diagnostic MBR, test points and related test information associated with components can be established.

The complexity of the model can be developed to the level necessary to perform the diagnosis. Components can have multiple sublayers if diagnosis is done to that level. For example, if a circuit board is completely replaced when found at fault then the model may show the circuit board as one component. If, on the other hand, individual elements on the circuit board can be diagnosed and replaced then the circuit board can have a sublayer composed of components for each circuit board element. An example of a model structure used in the "diagnostic assistant" program is given in Figure 1-1.

The use of MBR techniques has several advantages. Extremely complex systems can be diagnosed through the use of models. MBR does not necessarily require existing expertise to support diagnosis and can therefore be used with new systems or components. Also this approach shows good flexibility in response to changes in the system.

Expert system technology is based upon the use of existing expertise developed through experience. This expertise is documented from railcar maintenance experts in the form of expert rules. The process of interviewing experts and developing the information into computer rules is termed knowledge engineering. The rules generally take the form of "if-then" statements. The expert system rules are usually developed by experts after having seen similar conditions and faults many times. The rules then appear as "if this symptom is seen, then this is the cause of the fault."

The use of a rule-based expert system allows the capture of expertise from maintenance personnel who have been performing diagnosis for many years. Often this expertise is not documented anywhere and can be lost from the transit authority when the expert changes employment or retires. The knowledge engineering process of developing the rules through interviews with experts has an added benefit. It makes the diagnostic process, including testing and sensor data requirements, more visible. This often results in changes being suggested to diagnostics, maintenance, and occasionally even design of the railcars.

In diagnostic expert systems, the rules are often supplemented with probabilities related to failure of components. The probabilities can be developed from interviews with the experts or from historical maintenance data. The use of historical data requires that the data be partitioned in the same fashion as the diagnostic program. A good AI diagnostic program will actually change probabilities as the program is used to perform

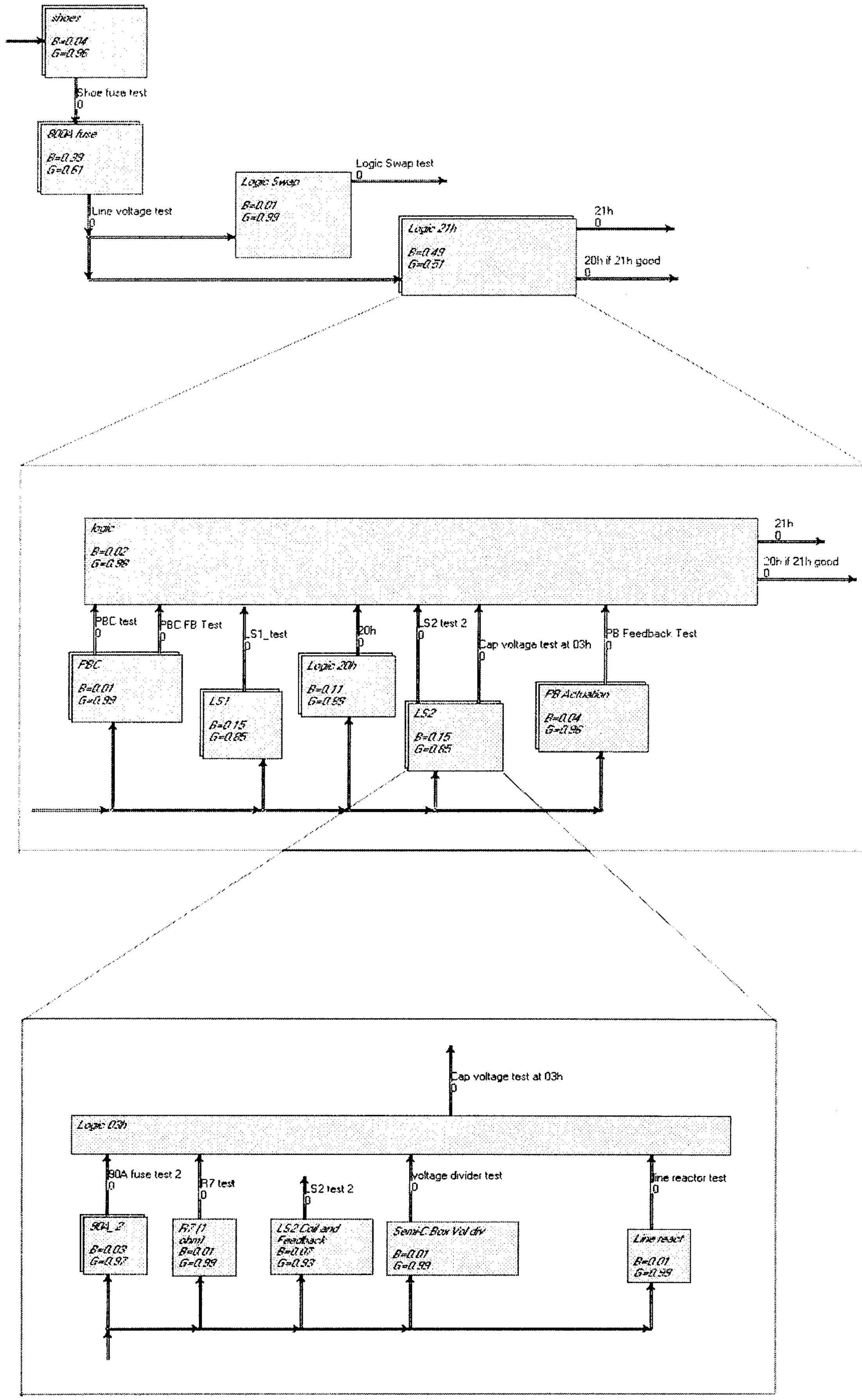


Figure 1-1. Example of Model Structure.

diagnosis. Consequently, the probabilities can be initially equal. Figure 1-2 provides a sample of rules from the "diagnostic assistant" program.

```
1.  (store-dimensions '("Blowing air" "Logic code" "Operational"))
2.  (store-preconditions
3.  '("Check if air is blowing" "Look at 21h, 87=good"
4.     "Check for 37V at MCJ1-R "
5.     "Test LS1s operation and HV circuitry for continuity."
6.     "Remove LS Box cover and perform ohm check of
    90A fuse."
7.  (store-cost '"Check if air is blowing" 00.10)
8.  (store-cost '"Look at 21h, 87=good" 01.50)
9.  (store-cost '"Check for 37V at MCJ1-R " 00.50)
10. (store-cost '"Test LS1s operation and HV circuitry for
    continuity." 03.00)
11. (store-cost '"Remove LS Box cover and perform ohm
    check of 90A fuse." 03.50)
12. store-expert-rule '(testpoint "Friction brakes test")
13.      '(dimension "logic code")
14.      '(preconditions "Look at 20h, should be 3E")
15.               '(outcome (name "20h = 1E")
16.               (causes (bad '"Temp Logic" 00.300)
17.               (bad '"Temp Sensors" 00.700)))
18.               '(outcome (name "20h = 3F")
19.               (causes (bad '"Slip/Slid Logic Problem"
                  00.200)
20.               (bad '"friction brakes" 00.800))))
```

Line	Explanation
1	Testing dimension (e.g. "voltage", "current", etc).
2-6.	Preconditions is a list of one or more setup procedures which must be done first.
7-11.	Cost is the cost of doing the test, includes time, equipment used.
12.	Test point name ("Friction brakes test").
13.	What is dimension of the test (voltage, current, visual inspection...).
14.	Condition for test to be good.
15.	1st possibility of test to be bad (20h=1E) – test can yield bad result in more ways then one.
16-17	Causes which can cause this condition and their probabilities.
18	2nd possibility 20h=3F.
19-20	Causes which can cause this condition and their probabilities.

Figure 1-2. Sample of Rules from the "Diagnostic Assistant" Program.

APPROACH

The demonstration described in this report was conducted in eight tasks described in the following paragraphs.

TASK 1. FIELD TEST SITE SELECTION

The first task of this effort was to select the site for the field test that would provide the greatest potential for successfully demonstrating the capability of the AI approach to diagnosis. A set of issues was developed to evaluate the transit agency's ability to support a successful field test. The transit authority which was best able to support the field test was recommended for approval.

The following list of issues important to a successful test was used as the criteria.

- Transit authority's willingness to participate in the project,
- Commitment by the transit authority to the success of AI diagnostic approach,
- The impact of propulsion system faults at the field technician level on the transit authority,
- Transit authority's use of DC chopper propulsion system (the project panel selected DC chopper as the basis for the project).
- Experienced diagnostic expert of propulsion systems available at the transit authority to support knowledge engineering activity,
- Propulsion manufacturer's participation in knowledge engineering activity,
- Collection and use of propulsion system variables,
- Historical data of diagnosis of propulsion systems,
- Management Information Systems (MIS) supports diagnosis of propulsion systems,
- Labor environment supports development of computerized diagnostic assistant,
- Maintenance technicians are comfortable using computers, and
- Maintenance technicians are available to test human-computer interface.

TASK 2. EVALUATION OF CURRENT MAINTENANCE FACILITY SYSTEMS

The primary purpose of this task was to determine what data and knowledge are available for use in the AI diagnostic program. Management, maintenance technicians, and MIS personnel were interviewed, and many potential sources of data and knowledge at the transit facility were identified. Current diagnostic procedures, data collection activities, and reporting practices related to diagnosis were identified. In addition, the potential for future integration of the software into the MIS environment were explored. Requirements for reporting diagnostic-related information was identified. The following list illustrates examples of the components that were investigated.

Maintenance Information System
Current diagnostic and maintenance procedures and locations,

- Historical maintenance databases;
- Diagnostic and maintenance reports;
- Automatic event-logging capability;
- Test equipment;
- On-vehicle sensors,
- Technical support information such as manuals, training material, and schematics; and
- Levels of diagnosis performed (e.g., car, system, subsystem, component, element in/on components).

TASK 3. HARDWARE AND SOFTWARE ACQUISITION

Development and demonstration of the AI diagnostic program required the acquisition of supporting hardware and software. The categories are listed below.

Hardware:
Desktop Development System
Laptop Runtime System
Supporting Hardware

Software:
Commercial Off The Shelf (COTS) AI Shell
Supporting Software

A single desktop development system was purchased along with three laptop systems. The category of support hardware refers to additional hardware needed for data acquisition and display. The primary software required was a commercial AI shell. An AI shell is a software program that stores, manipulates, and reports knowledge. Licenses of the AI shell were for the development system and runtime systems. The development license was needed for the desktop development system, and the runtime licenses were acquired for the laptops. Support software refers to additional software needed for data acquisition and display.

TASK 4. DATA COLLECTION AND KNOWLEDGE ENGINEERING OF RAILCAR PROPULSION SUBSYSTEM

Knowledge used in the AI diagnostic program came from multiple sources. Manuals, guides, training material, schematics, and other material identified in Task 2 were reviewed. This information was used to develop functional and causal models of the propulsion subsystem and its components. The models were developed in the COTS AI shell. The propulsion diagnostic experts reviewed the models and exercised the initial AI diagnostic program (using model information only). The experts made recommendations for modification to the models and suggestions for developing the human-computer interface for Task 6.

Interview sessions with the propulsion diagnostic experts contributed to the development of diagnostic rules. The rules were installed into the AI shell to enhance the "diagnostic assistant" beyond the models. The experts were again asked to exercise the enhanced program to determine if the models and rules were working together to produce the correct test suggestions and diagnosis. Historical propulsion system failure data was made available by the transit authority for a two-year period. An analysis of this data was used to develop the initial probability distribution.

TASK 5. ESTABLISHMENT OF A DIAGNOSTIC BASELINE

To demonstrate the impact of the "diagnostic assistant" program, the development of a propulsion system diagnostic baseline was investigated. Two comparisons were considered: (1) human performance to the AI program and (2) diagnostic time and accuracy of maintenance technicians operating without the AI diagnostic program to them operating with the program.

The nature of the diagnostic baseline was, in part, dependent upon the data available from the transit agency. The historical data were evaluated to determine if it could be used for a quantifiable diagnostic baseline.

Additionally, the use of propulsion system maintenance training exercises was also evaluated. There was an investigation to determine if a training set of problems could be used for comparisons to the AI diagnostic program with information about time to complete or probability of a correct diagnosis. Alternatively, the AI diagnostic program could be exercised against the training set of problems and qualitatively compared to expected human performance.

TASK 6. HUMAN-COMPUTER INTERFACE PROTOTYPE

An important aspect of the AI diagnostic program is acceptance by the end users, the maintenance technicians. The program not only must be able to help them diagnose propulsion faults correctly in a timely manner, but it also must be fairly easy to use. The human-computer interface (HCI) must be constructed so as to promote the use of the AI diagnostic program. End user input was necessary to help define the HCI. The commercial AI shell interface was exercised and critiqued by maintenance technicians. Modifications were made to the prototype.

TASK 7. TRAINING AND DEMONSTRATION

Training was provided to the transit agency maintenance technicians at various maintenance facilities. Several demonstrations were conducted for maintenance technicians and management personnel.

TASK 8. OPERATIONAL TEST AND EVALUATION

The three laptop runtime diagnostic systems were given to maintenance personnel. They used the systems to perform diagnostics when railcar propulsion system failures occurred. Additionally, critique sheets were distributed. Data were collected from the tests performed and the information in the critique sheets was compiled. Figure 1-3 illustrates the critiques sheets distributed. Evaluation of the "diagnostic assistant" was performed based upon the data of the operational test and the information compiled from the critiques sheets.

AI SOFTWARE CRITIQUE FORM

FSR No.	
Car No	
Discrepancy:	
Symptoms Displayed:	
Problem Found:	

	COMMENTS
Remarks:	
Is the software helpful?	
❐ Not Helpful ❐ Somewhat Helpful ❐ Helpful ❐ Very Helpful	
Are you comfortable using the software?	
❐ Not Comfortable ❐ Somewhat Comfortable ❐ Comfortable ❐ Very Comfortable	
Did the software suggest additional testing beyond your recommendation?	
Did the software recommend an inappropriate test?	

SUPERVISOR'S COMMENTS	
Level of technician's experience on 3000 Chopper?	❐ Inexperienced ❐ Somewhat Experienced ❐ Very Experienced
Do you feel software allowed more flexibility in work assignments?	❐ Yes ❐ No COMMENTS

Figure 1-3. Program Critique Sheet.

CHAPTER II

RESULTS

FIELD TEST SITE SELECTION

INTRODUCTION

Initially, all transit agencies were considered candidates for this effort. In consultation with the Transportation Research Board (TRB) and the project panel, it was decided that the emphasis should be focused upon direct current (DC) chopper technology. The DC chopper railcars use older technology, which is no longer manufactured. There are, however, still a large number of DC chopper technology railcars in service, and they account for a large portion of diagnostic difficulty, with little or no advanced technology diagnostic tools. It was believed that if this project could improve DC chopper diagnosis, considerable money could be saved.

The decision to focus on DC chopper technology reduced the list of potential field test sites to nine. The nine transit systems were contacted to discuss their desire to participate. The following is a list of the nine transit systems contacted. Prior to the telephone survey, an estimate of transit staff time required was sent to each system. The survey provided the estimated transit staff time needed to support this effort.

Metropolitan Atlanta Rapid Transit Authority (MARTA)
Atlanta, Georgia

Maryland Mass Transit Administration (MTA)
Baltimore, Maryland

Massachusetts Bay Transportation Authority (MBTA)
Boston, Massachusetts

Greater Cleveland Regional Transit Authority (RTA)
Cleveland, Ohio

Los Angeles County Metropolitan Transportation Authority (LACMTA)
Los Angles, California

Metro-Dade Transit Agency (MDTA)
Miami, Florida

Southeastern Pennsylvania Transportation Authority (SEPTA)
Philadelphia, Pennsylvania

Bay Area Rapid Transit District (BART)
Oakland, California

Washington Metropolitan Area Transit Authority (WMATA)
Washington, DC

Table 2-1 provides estimates of time required for transit personnel by task.

Table 2-1. Summary Table of Estimated Time Required from Transit Personnel

TASK NUMBER	PERSONNEL CATEGORY	NUMBER OF ESTIMATED HOURS	COMMENTS
Task 1	Maintenance Manager, Diagnostic Expert	12	Review and discuss this document, assist developing schedule
Task 2	Manager, Diagnostic Expert, MIS Personnel	16	Look at Knowledge Sources
Task 3	Manager	1	Discuss Hardware Issues
Task 4	Diagnostic Expert	100 - 400	Most difficult to estimate, interviews, develop rules, review models, exercise program
Task 5	Manager, Diagnostic Expert, Maintenance Technician, MIS Personnel	40 - 80	Depends on data available and approach taken
Task 6	Diagnostic Expert, Maintenance Technician	40	Test the interface and provide feedback
Task 7	Maintenance Technician, Diagnostic Expert, Manager	4 (per person for training) 12 for demonstration (preparation & demo)	
Task 8	Maintenance Technician	8 per technician for pre-prepared test	Practical test will occur through normal maintenance activities

CONTACT RESULTS

Four transit systems, BART, MBTA, Cleveland RTA, and LACMTA expressed interest in the project. They stated, however, that the staff commitment necessary to support the project was not available at this time.

The other five transit systems, MARTA, Baltimore MTA, MDTA, SEPTA, and WMATA agreed to be considered candidates for the field test. They all strongly supported this effort and stated that they would commit the necessary resources to it. These five transit systems provided similar information related to the list of discussion topics. They all have implemented MIS support, maintain historical maintenance information, have at least one propulsion diagnostic expert, and have maintenance technicians who are supportive of this effort. They are all adversely impacted by propulsion system faults and believe that a "diagnostic assistant" program could help reduce cost and increase availability of the cars. Table 2-2 lists the current number of railcars using DC chopper technology.

Table 2-2. Number of DC Chopper Railcars at Transit Authorities

MARTA	238
Baltimore MTA	100
MDTA	136
SEPTA	141
WMATA	400

SITE SELECTION

All five transit systems who were willing to participate have the environment and commitment necessary to help develop the AI diagnostic program. To maximize the probability of success, however, it was recommended that the effort take place at WMATA. It was felt that the large number of DC chopper cars operated by WMATA would provide fertile ground for experiencing a broad range of propulsion system faults, and a successful AI diagnostic program would have significant impact on the fleet. Additionally, the close proximity of WMATA to the development team allowed frequent interaction with the diagnostic experts and the maintenance technicians. The recommendation was approved by the project oversight panel.

EVALUATION OF CURRENT MAINTENANCE FACILITY SYSTEMS

INTRODUCTION

The WMATA maintenance environment was evaluated for potential sources of data and knowledge that could be used to develop the AI diagnostic program. Maintenance managers and technicians were interviewed. The railcar design and maintenance documentation were reviewed, as well as the maintenance data stored in the Maintenance and Reliability Systems (MARS).

ON-BOARD SENSORS AND EVENT LOGGING

The transit railcars at WMATA which utilize DC chopper technology are designated as 3000 and 4000 series cars. The propulsion systems of the two series are close to identical. A major component of both series is a logic control box which receives input information from the system. The 4000 series cars employ more of the logic control box memory location than the 3000 series. Additionally, the 4000 series logic control box can log 1.5 seconds of parameter values occurring prior to an event (e.g., out of range value which may indicate a fault).

For the 3000 series railcars, use of the on-board sensors must be done while the car is running under test. A two-digit light emitting diode (LED) read out on the logic control box shows a coded output from specified addresses. The addresses correspond to input points from sensors located in the propulsion system. The difficulty in using this information is that there is no provision for saving or storing the data, and in most cases the LED read out changes too quickly (up to 275 Hz) for the technician to get any value from it.

Railcars of the 4000 series have the capability to store 1.5 seconds of data, up to 1 kilobyte.

CURRENT MAINTENANCE PROCEDURES

The field maintenance process at WMATA begins when an operator of the train detects an anomalous event which is described as a fault or failure. The operator reports the problem to Operations Control Center which designates an event. The car is assigned to one maintenance technician who fills out a maintenance form (Figure 2-1) by entering a "failure description."

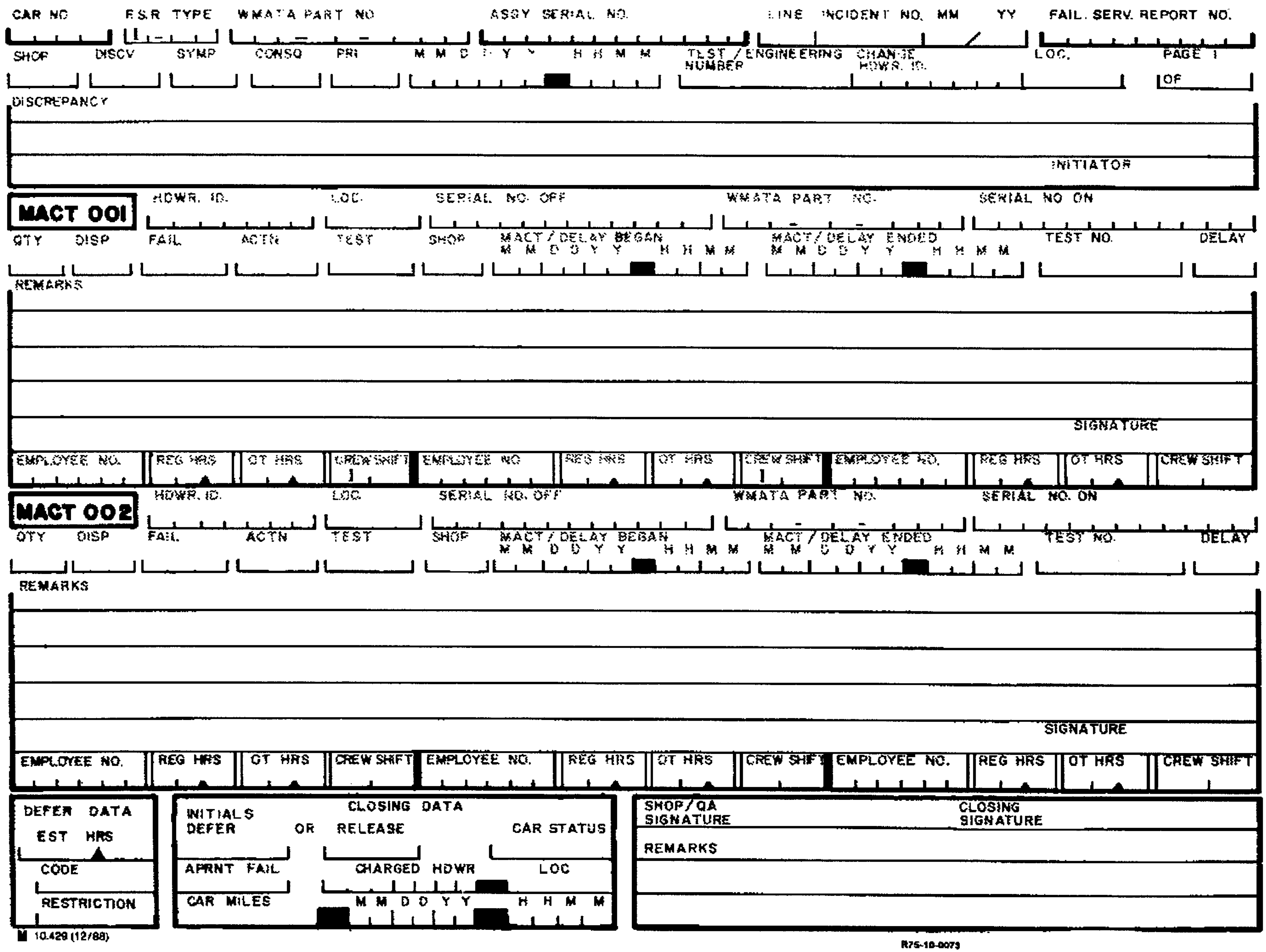


Figure 2-1. Maintenance Action Form.

The maintenance technician may access the MARS system to determine the maintenance history of the car. The technician may also access the logic control box to get information from the LED read out. Often the historical information will not shed light on the fault and the data from the logic control box will not be useful. The result is that the technician frequently relies upon his experience to determine the fault. If the technician is not able to start maintenance on the car immediately the car will be put aside. In some cases the faulty component will cool and will not repeat the fault resulting in a "no defect found."

The WMATA MARS (Maintenance and Reliability System) has the sixteen "codes" as shown in Table 2-3 below. The first twelve codes, 04a - 041, are fault codes.

Table 2-3. MARS Codes

04a	fails to operate (not MOL)
04b	motor overload (reset)
04c	motor overload (no reset)
04d	low power (sluggish operation)
04e	erratic operation
04f	failed test
04g	no dynamic braking
04h	no current indicator
04i	low current indicator
04j	high current indicator
04k	master controller defect
041	over temperature indicator (TCR)
04v	modification/retrofit
04w	test
04x	inspection
04z	no applicable code

TEST EQUIPMENT

Test equipment that can be used on the propulsion system at large is limited and difficult to use. There is test equipment for the circuit boards in the logic box, however, the logic box is replaced as a complete unit at the field maintenance level if it is suspected of having a fault.

The other test equipment consists of a paper chart recorder and a thyristor-diode tester. Both of these pieces of equipment are very difficult to use and often of minimal effectiveness. Consequently, they are often not used.

COMPUTER SYSTEM

The MARS system is hosted on a mainframe computer. The database management system software is Datacom used with supporting COBOL software. This system is about fifteen years old and the direct interface to the "diagnostic assistant" would require extensive effort. Specific data were transferred, however, from MARS to the diagnostic program via disk without too much trouble.

HISTORICAL DATA

The WMATA MARS system maintains historical maintenance data in a database. The data relates to specific cars, the maintenance code (symptom) described above, and the action taken, among other data. Figure 2-2 provides a sample of the data.

MAINTENANCE REFERENCE DOCUMENTATION

The documentation available to maintenance technicians and provided for this effort consists of the following books:

- Transit Car Parts Catalog,
- Transit Car Running Maintenance Manual,
- Heavy Repair Manual I,
- Heavy Repair Manual II,
- Heavy Repair Manual III,
- Detailed Description of Logic Control Box, and
- Monitor Module Manual.

TRAINING

WMATA provides a two-day training course in DC chopper technology. This course is given to new maintenance personnel and is recommended as a refresher course every few years for all. The knowledge engineer assigned to this task attended this course at the beginning of data collection phase.

HARDWARE AND SOFTWARE ACQUISITION

The development of the AI diagnostic program required the acquisition of a desktop development system and three laptop run time systems. For the development system a Pentium Pro 180 MHz based computer was acquired. For initial run time testing three Pentium 150 MHz, 12.1-inch screen, laptops were acquired. In purchasing the laptops special care was taken in choosing a rugged system with a relatively large screen. The software needed to develop and run the "diagnostic assistant" was a commercial off the shelf AI shell; Intelligent Computer-Aided Troubleshooting (ICAT). The cost of equipment is summarized in Table 2-4.

```
"952120117",1,"M","R18325036","518304","3E30000","FR
NT",728194
"952120117",1,"R","R18325075","078402","3E3A000","FR
NT",653215
"952120117",2,"A","R18325075","138405","3E3A000","FR
NT",728194
"952120117",2,"M","R18325036","518304","3E30000","FR
NT",728194
"952120117",3,"M","3E10000","3091","3E10000","NONE",
728194
"952120117",3,"R","R18325042","408305","3E1A000","NO
NE",539187
"952120117",4,"A","R18325042","198402","3E1A000","NO
NE",728194
"952120117",4,"M","3E10000","3091","3E10000","NONE",
728194
"952120117",5,"M","R18325036","508301","3E30000","RE
AR",728194
"952120117",5,"R","R18325075","188401","3E3A000","RE
AR",610760
"952120117",6,"A","R18325075","479009","3E3A000","RE
AR",728194
"952120117",6,"M","R18325036","508301","3E30000","RE
AR",728194
"952120117",7,"M","R18355003","9A4516","3K10000","FR
NT",614832
"952120117",8,"M","3E00000","3091","3E00000","BCAR",7
28194
"952120117",9,"M","R18325549","348315","3E1B000","NO
NE",678376
```

Figure 2-2. Sample of MARS Data.

Table 2-4. Hardware and Software Costs

Development Platform	Cost
Pentium Pro 180 MHz Desktop Computer	$2,800.00
AI Shell Software	$25,000.00
AI Shell Manufacturer Support	$5,000.00
Diagnostic Equipment	$1,400.00
Run-Time Platform	**Cost**
Pentium 150 MHz Laptop	$2,200.00

The AI shell requires the ability to run tests upon specific components within the propulsion system. The DC chopper configuration precludes the testing of various test points within the propulsion system. As described earlier, system sensor data are available in the logic control box but not easily accessible through the current test equipment. Since access to those data is almost equivalent to monitoring the test points, additional hardware and software were needed to read and store that data. To develop this capability, a Data Acquisition Card, DAQ Card-700 (100 kS/s sampling rate, 8 differential inputs, input range +/- 10 V) and Virtual Bench software package made by National Instruments, for the laptop system were acquired. With the appropriate connecting cables and voltage divider, the card acts to capture the data from the logic control box or logic terminal board assembly, and provides it to the laptop for display and storage. The DAQ Card can convert analog-to-digital and digital-to-analog data with appropriate speed in real time. A software package, VirtualBench-Scope, allowed display of the data in high resolution and real time. Figure 2-3 illustrates the interface display of VirtualBench-Scope.

DATA COLLECTION AND KNOWLEDGE ENGINEERING

INTRODUCTION

The "diagnostic assistant" is based upon a hybrid AI approach combining model-based reasoning and expert system techniques. The knowledge for the model and rules are developed through the knowledge engineering process and stored as a knowledge base. The model of the propulsion system was initially developed from schematics and descriptions found in the WMATA maintenance manuals. The model was then refined and modified through discussions with maintenance and engineering experts. The AI shell software automatically generates a set of rules from the models governing the process. Additional rules were developed through interviews with the maintenance experts and added to the knowledge base.

MODEL DEVELOPMENT

The core of the AI diagnostic program is the propulsion system model of the DC chopper propulsion system used at WMATA. The model includes component names, inputs and outputs, test points and test information, and the probability of any component being good or bad. The initial model was developed mainly from the maintenance reference manuals

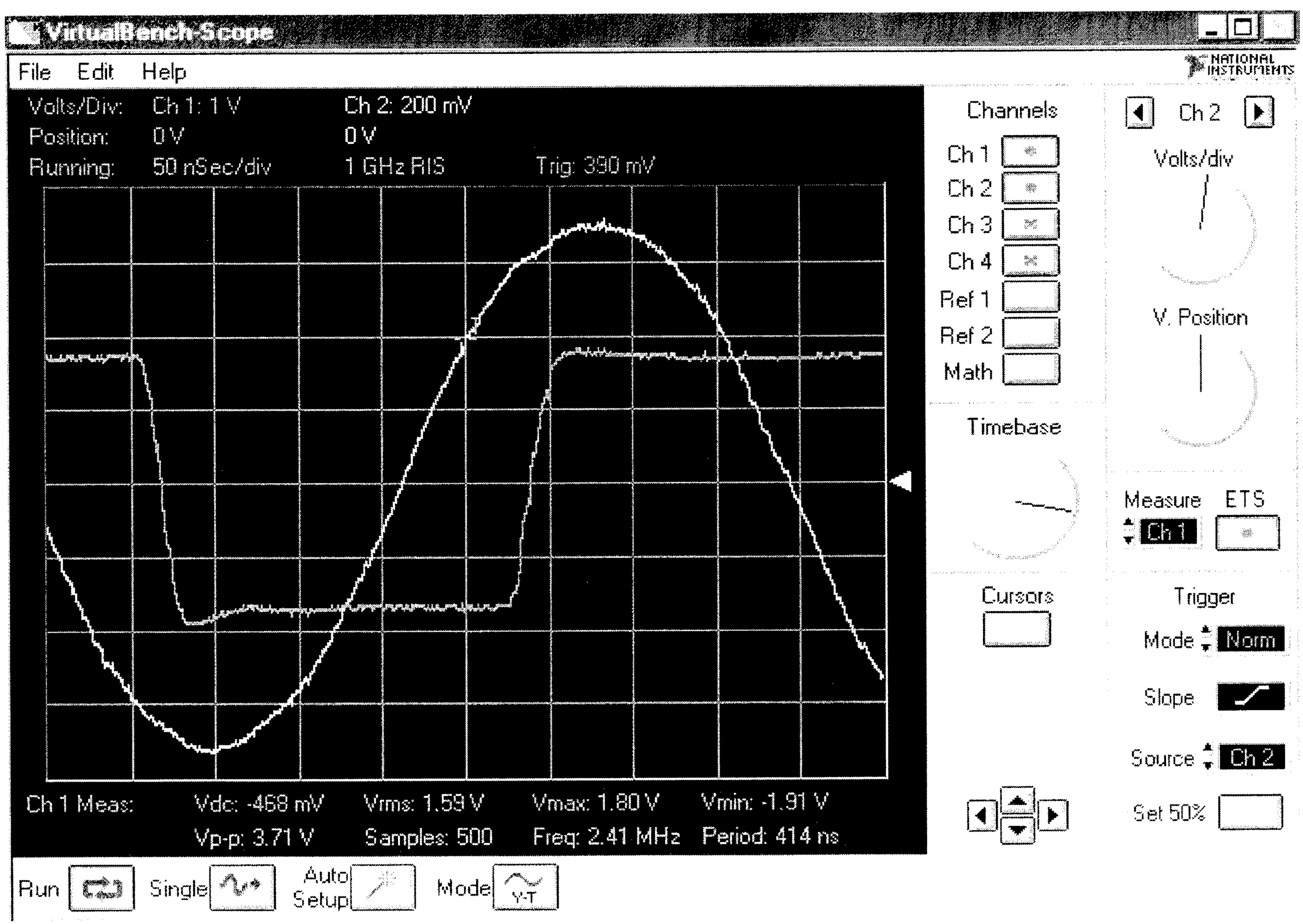


Figure 2-3. Sample Screen of VirtualBench-Scope Package.

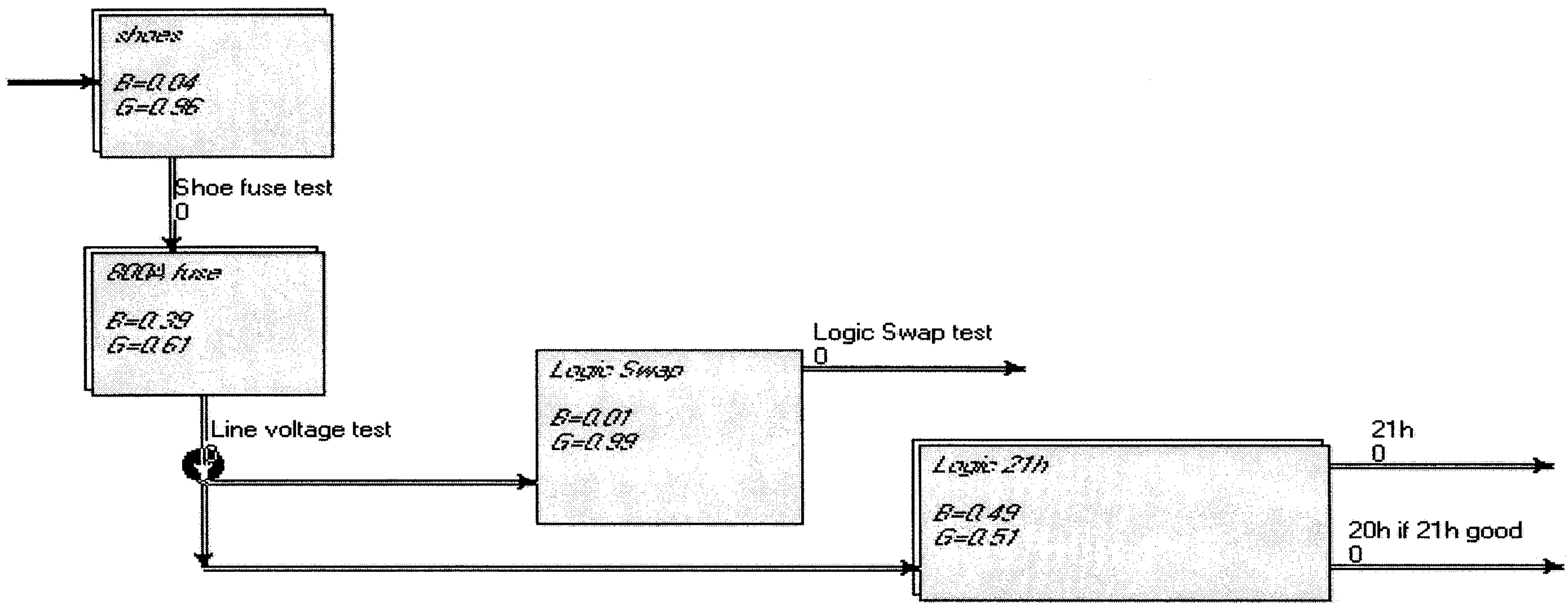


Figure 2-4. Sample of the One-Level Model.

supplied by WMATA. An example of one level of the model is depicted on Figure 2-4. The gray boxes represent subsystems or components. Boxes with double lines indicated that there are further levels of detail within that box. For example, the subsystem "800A fuse" is composed of six replaceable components, and "Logic 21h" subsystem consists 56 replaceable components.

Based on review and comments of the initial one-model approach by the WMATA experts, it was found to be overly complex and hard to use. It was decided to modify the initial one-model approach and to break it down into seven smaller sub-models. A modular approach was consequently used for the development of the whole system. It was constructed as a number of separate smaller systems (sub-models) that are evaluated only when triggering conditions for the sub-model are satisfied. In this case the triggering conditions were chosen to be displayed symptoms. This structure reduced redundant evaluation of components that could not be the cause of a particular displayed symptom.

The seven sub-models represent the entire propulsion system, and they are accessed through the displayed symptoms. The seven sub-models are named by symptom: No or Low Current Draw, Jerking in Propulsion, Jerking in Braking, No Dynamic Braking, Motor Overload (MOL), Flashing MOL, and Friction and Dynamics.

The seven symptoms were selected because some of them have been used by WMATA as symptom codes for Failure Service Reports (FSR) for many years. This greatly facilitated assigning initial probabilities in the model.

Some separate symptoms used by WMATA were combined in the models. This was because some of the symptoms could be induced by the same components. This was case with symptoms "No Current Indicator" and "Low Current Indicator."

On the other hand, some single symptoms used by WMATA were found to be too broad for the models. This was the case with symptom "Erratic Operation." This failure can be manifested by many different characteristics. In the "diagnostic assistant" this symptom was divided into "Jerking in Propulsion," "Jerking in Braking," and "Friction and Dynamics." Any of these symptoms was considered as an "Erratic Operation" in the MARS database. Each of these symptoms is caused by a different component and has to be determined in a different way.

RULES

Rules have been used extensively in many AI programs. Many developers believe that rules closely represent the way humans deal with everyday problems, which make them easier to understand. Additionally, in an AI program, each rule can be considered independent of the others. This allows for ongoing construction of AI programs.

The AI shell software used in this project automatically generates a list of expert system rules. The rules correspond only to the attached model. The rules generated by the current model are in LISP programming language. A sample of generated rules and their explanation is shown in Figure 2-5.

```
1.(store-expert-rule '(testpoint "BOLR test")
2.      '(dimension visual)
3.      '(preconditions "look at 20h" "20h=3E is good")
4.            '(comment logic)
5.            '(cost 00.500000)
6.            '(outcome (name "20h=36")
7.                  (causes (bad 'BOLR 00.300000)
8.                        (bad 'PR_1 00.256295)
9.                        (bad 'ER 00.196295)))
10.           '(outcome (name "20h=34")
11.                 (causes (bad 'OLR 00.610000)
12.                       (bad 'GDR 00.291351)))
13.           '(outcome (name "20h something else")))
```

Line	Explanation
1.	test point name "BOLR test"
2.	what is dimension of the test (voltage, current, visual inspection...)
3.	condition for test to be good "20h = 3E"
4.	comment to help in the test procedure
5.	cost of the test (how much time or equipment is needed)
6.	1st possibility of test to be bad (20h = 36), test can yield bad result in more ways than one
7-9.	causes which can cause this condition and their probabilities
10.	2nd possibility 20h = 34
11-12.	causes which can cause this condition and their probabilities
13.	3rd possibility

Figure 2-5. Sample of Generated Rule in LISP and Explanation.

Following is an example of a combination of rules and fault modeling. Figure 2-6 shows a part of Motor Control Box Relay Logic that is responsible for providing a signal to Control Logic.

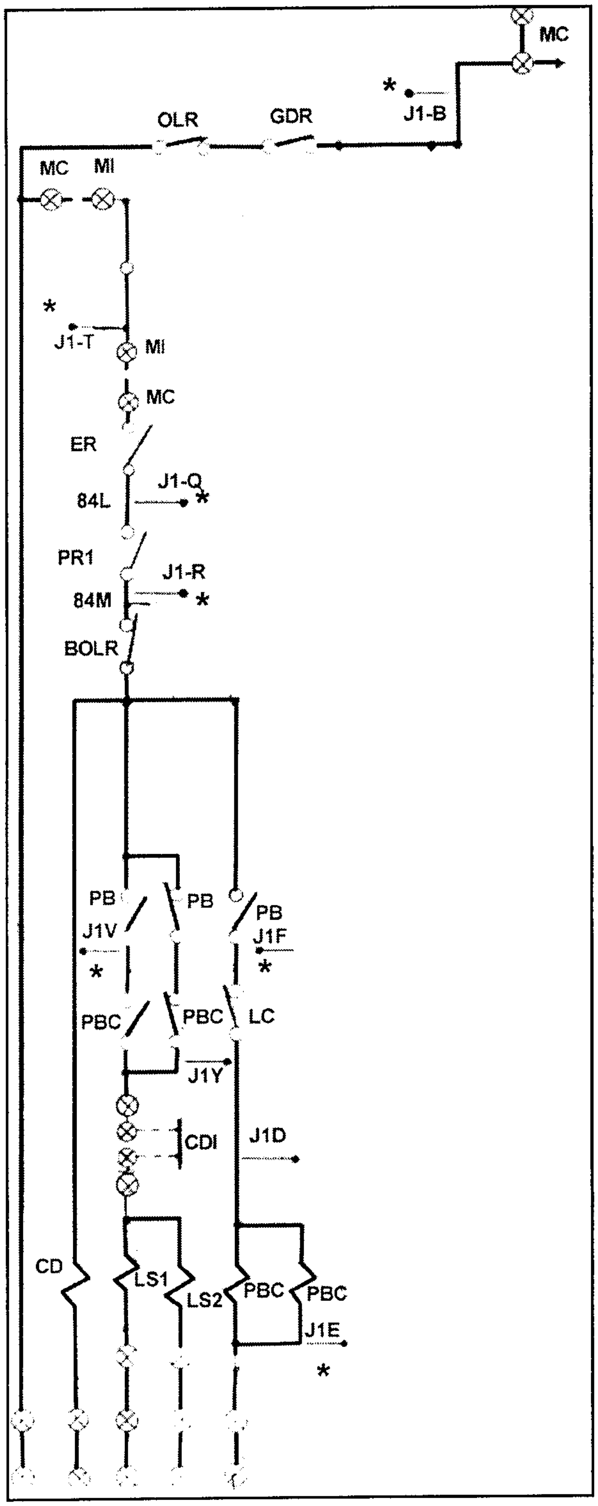


Figure 2-6. Motor Control Box Relay Logic (Partial Schematic)

Figure 2-7 represents the causal model for the previous figure. This signal will be either high or low, depending of positioning of many contacts. Each contact will be in the open or closed position that will represent the status of a certain component. The accessible test points are noted by an asterisk (*). WMATA has a diagnostic board, Control Logic XA7, that can be inserted into the Control Logic Box. This allows a technician to gather data from memory locations in the Control Box. The test point values can be obtained through the Control Logic XA7 board looking at the memory location 21h. Should a test of memory address 21h give a hexadecimal value of 84, this indicates that PB and PBC contacts are energized. Therefore, anything below (BOLR, PR1, ER, OLR, GDR) in the electrical circuit has to be working properly. Thus there is no need to spend time and effort in checking those components.

HISTORICAL DATA

The model-based approach to diagnosis uses probabilities of components being good or bad. The probabilities are updated for each component every time the program receives new information (e.g., a test result). A priori probabilities can be used if historical data are available. In WMATA's case, MARS provides the possibility of developing those probabilities for the 3000 and 4000 series cars. Determining the historical probabilities is not straightforward. This difficulty is due primarily to the differences in symptom and component categories between the AI model and those in MARS. A mapping for those items was developed using Microsoft Access. This provided a search capability through the MARS database. The search was done based on propulsion system symptom code and "Hardware Identification Number," i.e., which part was changed during maintenance. Correlation between these was established and later used in setting up the model's initial probabilities.

Starting probabilities for each of the models were first calculated from the MARS historical data for the last two years. These statistics were not very accurate due, in part, to the lack of detailed data. The component codes that are entered as replaced components can be very unspecific, such as "Miscellaneous Propulsion System" or "Propulsion Motor Control" which cover dozens of replaceable components. The data were modified to be more specific, after consultation with WMATA technicians. The following two figures show the probabilities developed for "No Current Condition." The probabilities in the Figure 2-8 were developed directly from MARS data. The probabilities in Figure 2-9 were developed after consultations with maintenance technicians and are those used in the "diagnostic assistant" model.

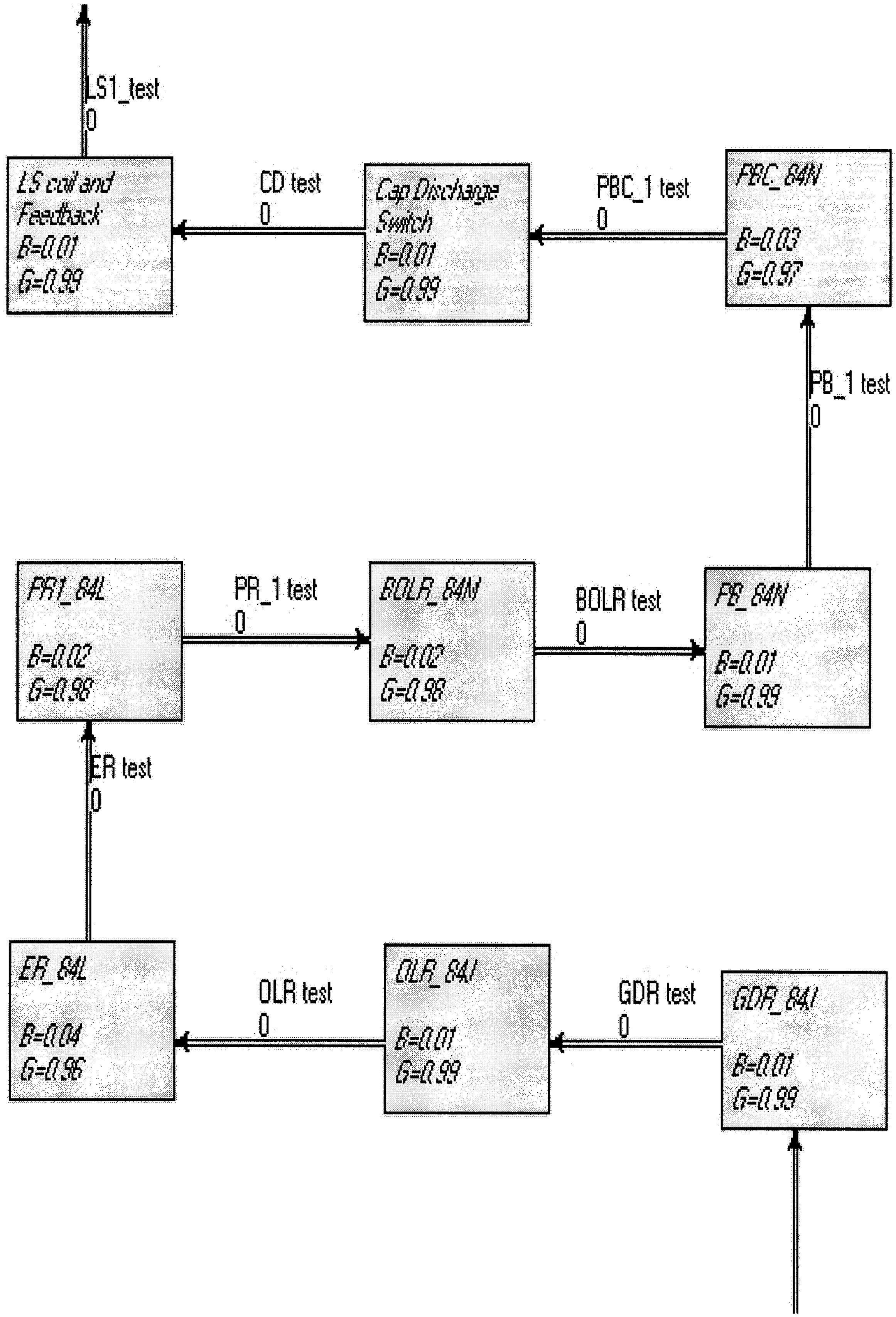


Figure 2-7. Causal Model of Schematic from Figure 2-6.

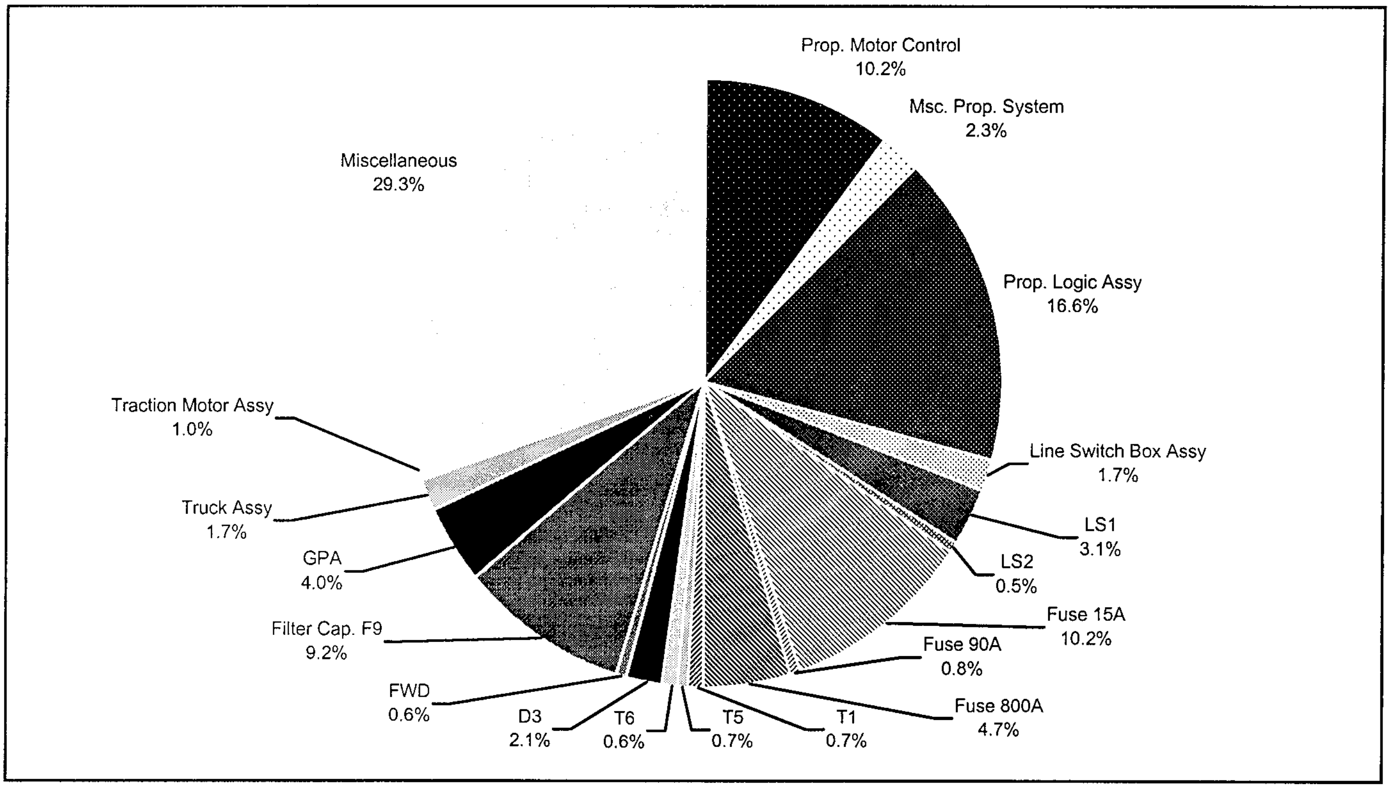


Figure 2-8. Probabilities for "No Current Condition" Based on MARS Data.

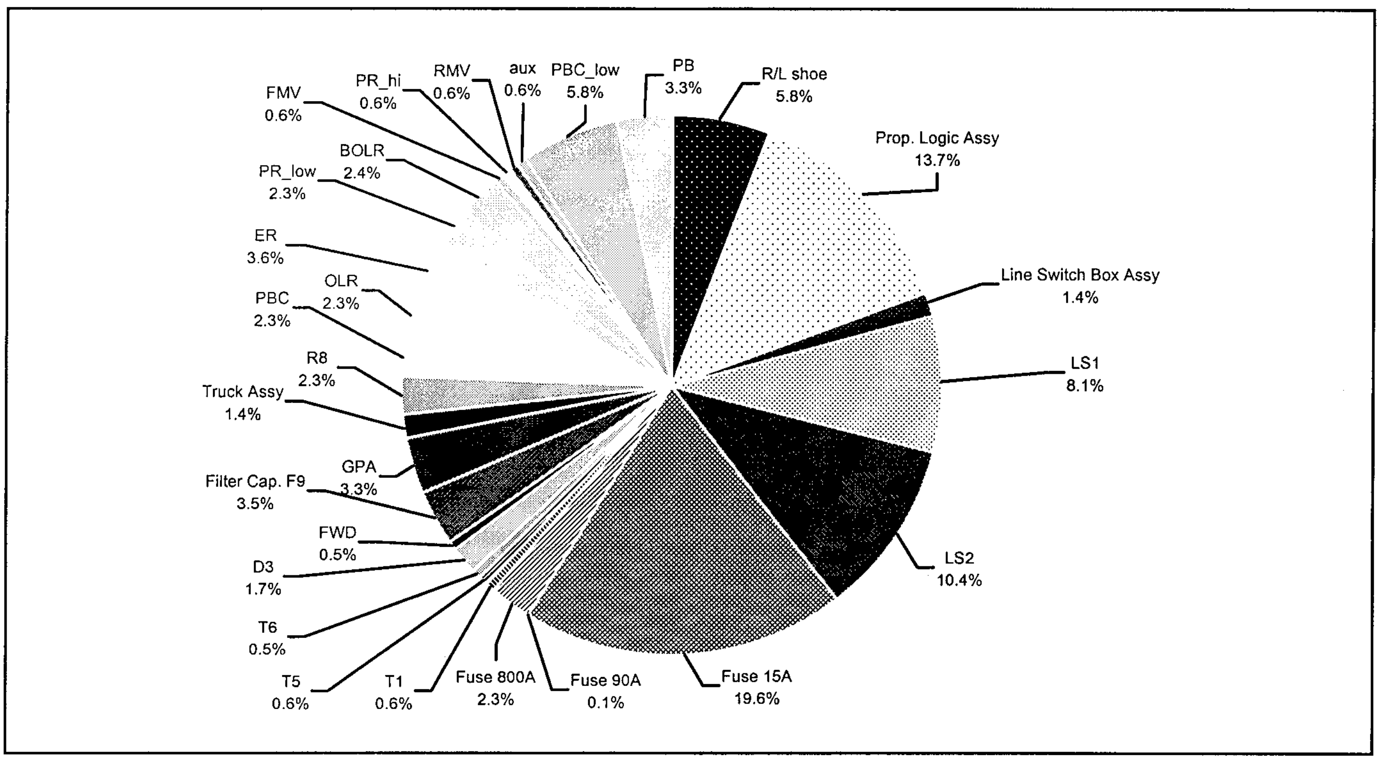


Figure 2-9. Probabilities for "No Current Condition" Used in Model.

The "diagnostic assistant" can continue to update its own historical data, in the form of probabilities, even if it starts with no a priori probabilities. In that case the program will assume equal probabilities for all components as its initial state. In the model every component has an initial probability to be good or bad. These probabilities are updated depending upon the chosen symptom and results of tests. After the program has successfully identified the faulty component, that information can be saved and used in each succeeding process. Figure 2-10 provides an example of probabilities used in the "diagnostic assistant." Each line represents one component and associated probability to cause the particular problem. For example, "store-fail-rate 'LS1 07.20000" means that Line Switch (LS1) has a probability of 7.2% to be the source of this failure. By default each connection, named as "J", has the probability of 0% to be the cause of this failure.

```
; ----- Sub-Structure Block Diagram -----
(store-fail-rate 'J20 00.000000)
(store-fail-rate 'J21 00.000000)
(store-fail-rate 'PBC 05.000000)
(store-fail-rate 'LS1 07.200000)
(store-fail-rate 'J30 00.000000)
(store-fail-rate 'PB 02.900000)
(store-fail-rate 'J12 00.000000)
(store-fail-rate 'LS2 09.250000)
```

Figure 2-10. Sample of "Diagnostic Assistant" Historical Data.

MODEL CHARACTERIZATION

In the AI diagnostics program, seven models were built. Each represents a part of propulsion system. The model names are as follows:

- Motor Overload (MOL),
- Flashing MOL,
- No or Low Current Draw,
- Jerking in Braking,
- Jerking in Propulsion,
- Friction and Dynamics, and
- No Dynamic Braking.

The seven models are presented in detail in Appendix B.

Motor Overload (MOL)

A Motor Overload (MOL) condition exists when one of three relays in the propulsion system's motor control box becomes energized. These relays are the Overload Relay (OLR), Brake Overload Relay (BOLR), and Ground Detect Relay (GDR). When any of these three relays become energized, normally closed contacts will open and disable the propulsion system, while a set of normally open contacts will become closed and illuminate MOL annunciation lights. OLR and BOLR provide protection of the propulsion system from excessive current. These two relays are set to trip at 1800 A. When tripped, the relays are mechanically latched and must be reset before the propulsion system can resume operation. The propulsion system logic control box energizes GDR when it detects a difference of more than 200 A between the current coming into the system and that which is returning to ground. GDR also becomes mechanically latched when energized. All three relays have an electrical reset coil that allows remote resetting by the operator.

There is an overload counter which will allow resetting of three overload faults. However, if a fourth overload occurs, the overload counter prevents the operator from resetting the MOL. When this happens, the train is said to be "MOLed out" and is removed from revenue service.

Flashing MOL

When the Control Logic detects an overload condition that is not hazardous, it energizes relay OLX in a cycling fashion which causes the MOL annunciation lights to flash. Also, the line switches on the affected car are opened causing the propulsion system to become de-energized. A Flashing MOL occurs when the Control Logic detects any one of a number of abnormal conditions. This can happen because of a hardware or software overload. Both types of overload cause the propulsion system to be de-energized. However, the Control Logic attempts to reset hardware overloads each time the train is stopped and in brake. Software overloads can only be reset by resetting the Control Logic, which is done by turning off all power (keying down).

A software overload is detected if any of the following conditions are detected:

- Motor current continues to rise too fast,
- Voltage across Dynamic Brake Resistor R5 is more then 256 volts for five seconds during operation in power,
- Transition from power to brake mode exceeds time limit,
- Computer memory RAM or EPROM error, or

- Chopper operating frequency exceeds tolerance of +/- 0.01%.

A hardware overload occurs whenever the following conditions are detected:

- Thyristor overheated,
- Emergency relay not energized,
- Confirmed directional relay de-energized, or
- Propulsion cutout switch in cutout position.

In addition to the above symptoms, if either of the following occur, then the propulsion system on the affected car will operate at minimum power, about 50 A.

- Blown line filter capacitor fuse or
- Excessive capacitor ripple voltage.

No or Low Current Draw
On the operator's indicator panel there is a dial that shows current flow in and from the car. When a car is working properly, during acceleration the current is flowing into the car and during dynamic braking the current is flowing out of the car into the system. In this model the only concern is with problems of drawing current in a power mode of operation. Dynamic braking problems were addressed in the No Dynamic Braking model, because these are two completely different problems caused by failure of different components.

Jerking in Braking
The symptom of Jerking in Braking can be described as anything other than a normal, smooth deceleration of the railcar while in braking mode. There are two methods of achieving this deceleration. One is by way of the Friction Brake System, where brake pads are applied with force against disks mounted on the wheel axle. The friction of the brake pads rubbing against the brake disks will produce and dissipate heat through the disks thus removing kinetic energy from the vehicle and causing it to slow down.

The second method of deceleration is achieved by configuring the Traction Motors in the propulsion system as generators. The resultant energy is then either dissipated as heat across a resistive load (Dynamic Braking), or fed back through the third rail to the system (Regenerative Braking).

For purposes of this project, the focus is on the second method. As it turns out, unless the Friction Brake System is clearly demonstrated to be the cause, the fault will always be reported to the maintenance shop as a propulsion-related failure. This is due to the fact that the propulsion system is most likely to be the cause.

Jerking in Propulsion
The symptom of Jerking in Propulsion can be described as anything other than a normal smooth acceleration of the Rail Car in power mode. There is usually no annunciation associated with this failure. The fault will be detected when the train operator, or a Road Mechanic, notices an abnormal operation of the affected car.

This failure can be divided into other symptoms, as there are different ways the "Jerking" operation can manifest. There are three symptoms. They are "Jerks at 35 mph," "Jerks at 45 mph," and "Jerks at Any Speed." The last symptom is further divided into two symptoms of "Shutter" and "Intermittent Jerking."

For each of the above symptoms the same Model is used. However, different probabilities and expert rules are employed to reflect the probability distribution for the specific failure mode. For example, the symptom of "Jerks at 35 mph" describes a failure where the car will jerk momentarily as it is accelerating and the car's speed reaches and passes 35 miles per hour. This is a very specific fault mode, which is almost without exception attributed to a failure of the F3 – F4 contactors in the motor control box. Therefore, when the technician loads the "Jerking in Propulsion" model and selects the "Jerks at 35 mph" symptom, the software is going to recommend testing of these two devices very early on in the diagnostic process.

Friction and Dynamics
As described in the characterization for the Jerking in Brake Model, there are two methods of decelerating the railcar. The first method is the Friction Brake System, and the second is Dynamic Braking. At speeds above approximately 12 mph, there will be enough Dynamic Braking effort to achieve the desired deceleration rate. In this normal operating condition, friction braking is neither needed nor preferred due to excessive brake wear.

The propulsion system provides a Dynamic Brake Feedback signal to the Friction Brake System proportionate to the level of actual Dynamic Brake effort. The friction brake system will use this signal to adjust the amount of friction brake effort being applied so that the sum of the two braking efforts will equal the total being requested. When the feedback signal indicates that there is sufficient dynamic braking to fully achieve the desired deceleration rate, the friction brakes will be fully released. The train operator can see by way of a "Brakes Released" indicator light on the operating console when this is so. Below 12 mph, the dynamic braking effort starts to decay. As it does, the friction brake system will proportionally increase the friction brake effort to maintain the desired brake effort.

The fault of "Friction and Dynamics" is detected when the operator notices the lack of a "Brakes Released" indication while in a brake mode with a train speed above 12 mph. It is then necessary to isolate the failure to the affected car. This is done by observing the current meter and brake cylinder pressure gauge on each car in the console. The car that shows both dynamic brake current and friction brake effort together with train speed above 12 mph is the failed car.

The actual cause of the failure can be within the propulsion system, the brake system or the wiring connecting the two. However, this fault is always treated as a propulsion system failure until it is found to be otherwise.

No Dynamic Braking

This fault mode is rather straightforward in that its name accurately describes the failure. Detection of this fault is initially the same as for "Friction and Dynamic" in that the train operator will note the lack of a "Brakes Released" indication while in brake mode with train speed above 12 mph. The difference is that the failed car will only show the presence of brake cylinder pressure. There will be no indication of dynamic brake current on the propulsion system current meter.

The models went through numerous reviews and refinements. WMATA training personnel and expert maintenance personnel reviewed the model for correctness and completeness. As the model was exercised, the correct level of detail for each subsystem and component was determined. The test points in the model were refined to correspond to those that can be used in the propulsion system. The data from those test points can be accessed through the logic control box with the DAQ card or in some other fashion.

DEVELOPMENT COSTS

The total time to develop the model was approximately one year. This includes the time required for researching the propulsion system and determining how the model is to be presented and processed by the software. While the Knowledge Engineer expended the most hours on the project the contributions of the Program Manager and the WMATA propulsion expert were invaluable. In addition, an Administrative Assistant also was instrumental in supporting the efforts of the project team. Labor for the entire project is summarized in Table 2-5.

Table 2-5. Development Level of Effort

Labor Category	Hours
Program Manager	500
Knowledge Engineer	2200
Administrative Assistant	800
WMATA Propulsion Expert	500

The total cost of labor was approximately $140,000.00. This does not include the time of the WMATA propulsion systems expert since they were provided by WMATA for this project. The hours expended by WMATA staff were approximately as estimated in Table 2-1.

DIAGNOSTIC BASELINE

Development of a quantifiable diagnostic baseline was attempted. The MARS data was evaluated in detail in an attempt to isolate diagnostic times tied to components. Additionally, it was hoped that symptom data could also be correlated to the maintenance entries. Unfortunately, the MARS data is not structured to support this approach. The data provides complete maintenance time which includes diagnosis, repair, and even in some cases time related to waiting for parts.

The symptom based categories used by the MARS database do not correspond well with those used in the "diagnostic assistant." Attempts to develop a diagnostic baseline in the form of time to diagnose, and accuracy of diagnosis for components based on symptoms were unsuccessful.

HUMAN-COMPUTER INTERFACE

OVERVIEW

In the "diagnostic assistant" the human-computer interface (HCI) is mainly defined by the COTS AI shell and VirtualBench software. Some minor customization of the Windows environment can be performed, however, it was found that technicians preferred having the interface already set. Generally, they liked software that can be launched directly from desktop icons. Some of the technicians were resistant to using any computers. This issue should become less crucial in future because of increasing familiarity with computer technology. Also, software companies are learning how to make more reliable and human friendly software.

USER OPTIONS DURING FAULT ISOLATION

After a test is chosen, the user is presented with a test procedure to perform. At each point in the fault isolation process, a number of options may be available for the technician to use. Figure 2-11 provides an example of the program interface that the maintenance technician uses when performing diagnosis.

The maintenance technician can interact with the "diagnostic assistant" in the following ways:

Recommended Test: The name of test that is presently recommended.

Setup Procedure: One-line tip of how to perform the desired test. If this is not helpful enough, a Help button is available for more detailed information.

Last Action: One-line information about the previously performed test.

Good: A test outcome of good that may be declared after the test is executed.

Bad: A test outcome of bad that may be declared after the test is executed.

Done: A test is performed, and the test result should be entered.

Don't Know: A test outcome is unknown. The program will choose the next most appropriate test point.

Forget: At any point during troubleshooting process, the user may back up and redisplay and repeat the last test. Repeated use of this feature can back up the troubleshooting procedure to any place in the sequence.

Pop-up: Exits the current level of the model to the level above it.

Sub Diagram: Exits the current level of the model to the level below it.

Help: It accesses on-line help files. A great amount of information, concerning the why, what and how of the current situation, is available through this option. For each test point there is a text file and when appropriate a picture file.

Quit: Quits a troubleshooting session.

During the fault isolation process, each test is timed and each test step in the diagnostic process is recorded in a log file for future use, if desired.

TRAINING AND DEMONSTRATION

The seven models and training materials were implemented with WMATA personnel over a three-month period beginning in April 1998. Training and demonstration of the "diagnostic assistant" was conducted at the three maintenance shops - Greenbelt, Shady Grove, and Brentwood. The same process was conducted at each facility, but the amount of time spent at each facility varied depending upon the number of attendees and the types of problems that were diagnosed.

First, a demonstration was conducted by the Electrical Engineer and the WMATA Maintenance Expert for WMATA management, supervisors, and technicians. An average of 15 people attended these sessions. This demonstration provided an overview of the tool and how it was to be used. Next, the Electrical Engineer and the WMATA Maintenance Expert conducted individualized training sessions with 2 or 3 technicians at each location with each session lasting 1 hour. After the training sessions were completed, the Electrical Engineer and the WMATA Maintenance Expert observed and assisted the technicians as they used the "diagnostic assistant" on actual propulsion system failures. These troubleshooting sessions varied in length from a half hour up to 4 hours depending upon the type of failure. It was found that the maintenance personnel learned very quickly how to use the "diagnostic assistant."

OPERATIONAL TEST AND EVALUATION

The WMATA maintenance technicians were given the "diagnostic assistant" and asked to use the program when performing maintenance against series 3000 propulsion system faults. There were approximately 144, 3000 series chopper propulsion system failures at

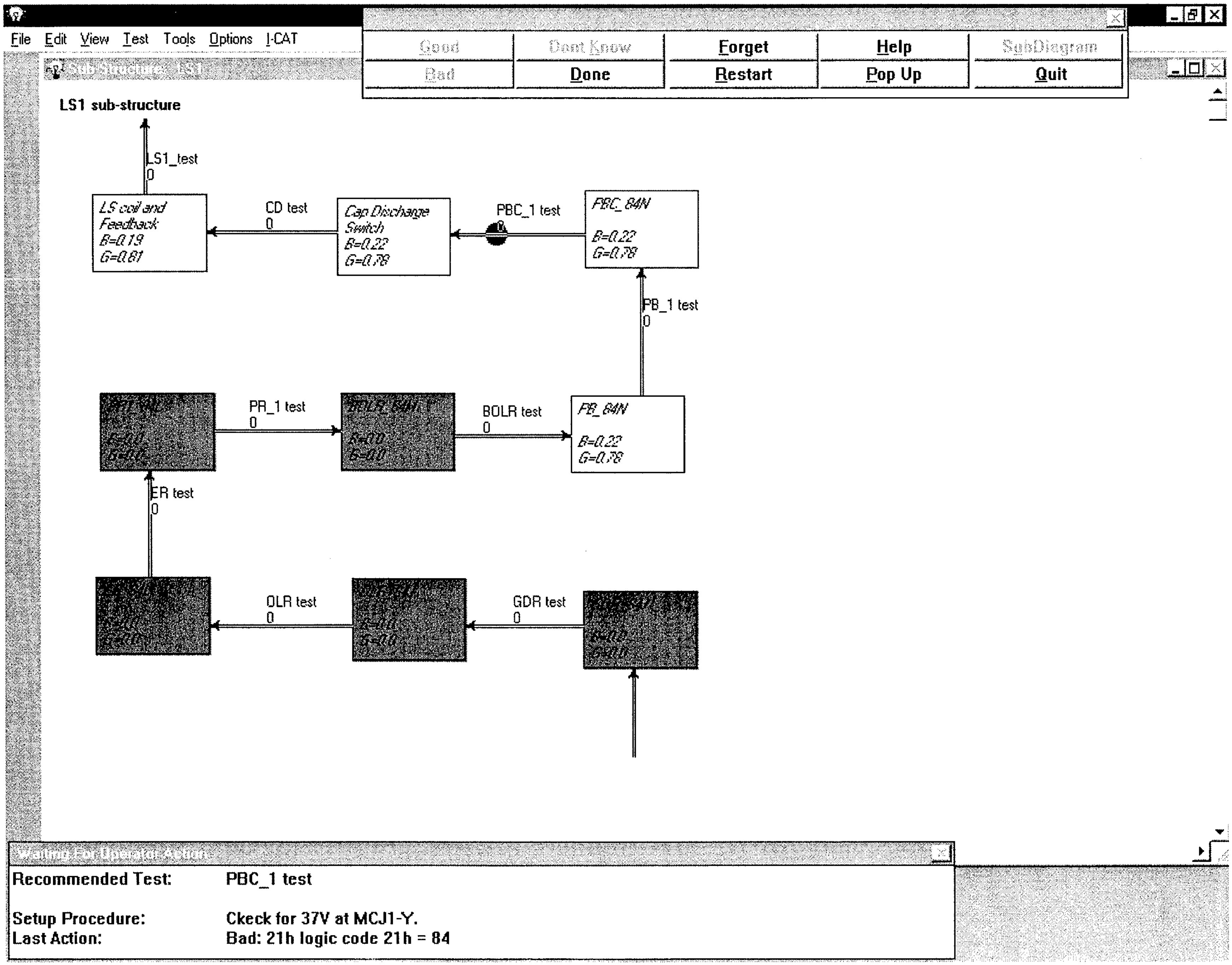


Figure 2-11. Example of User Interface Screen During Diagnostics Process.

the test sites during each of the 3 months of the test. The "diagnostic assistant" was used in diagnosing approximately 10% of these failures. The demands of the maintenance requirement to return the cars to service as quickly as possible created reluctance on the part of the maintenance technicians to use an unproven program. Workload and manpower concerns overrode those of the test.

The WMATA propulsion expert that assisted in the development of the model and rules participated in administering the test. His presence during the test provided official WMATA support and approval. Fifteen actual propulsion faults were diagnosed using the program. Table 2-6. presents the results of the test.

Of the 15 times the software was used, the program successfully isolated the failure 11 times. There was 1 instance where it was unsuccessful and 3 instances of "No Trouble Found" (NTF). On the unsuccessful run, it appears as if the failure was miss-reported. The failure was reported as a "No Current Draw." The problem found with the train would have caused a failure of "Flashing MOL." Had the Flashing MOL Model been run, the software would have found the failure.

Test number 15 in Table 2-6 demonstrated how the AI Diagnostic software effectively guided a technically competent individual who lacks specific system knowledge and experience to the cause of a given failure. A train had developed a failure of "No Dynamic Braking." The technician assigned to work on the problem had successfully completed the class on the 3000 Chopper. However, as this individual had very recently moved from the position of "Car Cleaner" to "Mechanic Helper Electrical," he had no previous troubleshooting experience on this, or any other system.

Using only the "diagnostic assistant" to guide him through the process, this individual successfully isolated and repaired the cause of the failure in minimal time. The train was released back into service and the failure did not reoccur.

The maintenance technicians who participated in the testing were asked to complete critique sheet (Chapter I, Figure 1-3). The results of the critique sheets are presented in Table 2-7.

The results of the tests and critique sheets indicate that the "diagnostic assistant" can be very effective in supporting the maintenance process. Most of the faults (11) were found using the "diagnostic assistant." The one case that failed may have been caused by an incorrectly reported symptom. The 3 cases of "No Trouble Found" illustrate the possibility of some faults that cannot be detected. These faults could be either intermittent faults (e.g., loose electrical connection), or faults whose symptoms cannot be reproduced due to maintenance restrictions (e.g., speed limited in maintenance yard to 15 mph.). The program recommended additional tests (9) that the maintenance technicians may not have pursued.

Table 2-6. Results of Propulsion Fault Diagnosis Using the "Diagnostic Assistant" Program

	Reported Failure	Symptom Found	Model Used	Failed Component	Software Successful?
1	**No Current**	**No Current**	**No or Low Current**	**90 A Fuse**	**Yes**
2	**Jerks in Braking**	**None**	**Jerking in Braking**	**Free Wheeling Diode**	**Yes**
3	**No Current**	**No Current**	**No or Low Current**	**800 A Fuse**	**Yes**
4	**Flashing MOL**	**None**	**Flashing MOL**	**T1A**	**Yes**
5	**Flashing MOL**	**None**	**Flashing MOL**	**None**	**NTF**
6	**MOL**	**Flashing MOL**	**Flashing MOL**	**Logic**	**Yes**
7	**MOL**	**MOL**	**MOL (GDR)**	**None**	**NTF**
8	**No Current**	**No Current**	**No or Low Current**	**90 A Fuse**	**Yes**
9	**No Dynamic Braking**	**No Dynamic Braking**	**No Dynamic Braking**	**PBC Cam Follower**	**Yes**
10	**Intermittent Current**	**None**	**No or Low Current**	**None**	**NTF**
11	**No Current**	**No Current**	**No or Low Current**	**Propulsion Logic**	**Yes**
12	**Flashing MOL**	**None**	**Flashing MOL**	**Free Wheeling Diode**	**Yes**
13	**No Current**	**Prop. Blower inoperable**	**No or Low Current**	**Loose wire at blower fuse**	**No**
14	**No Current**	**No Current**	**No or Low Current**	**800 A Fuse**	**Yes**
15	**No Dynamic Braking**	**No Dynamic Braking**	**No Dynamic Braking**	**Auxiliary Contact of PBC**	**Yes**

Table 2-7. Critique Results of "Diagnostic Assistant" Test (Number of Critiques = 15)

Is Software helpful?
Not Helpful – 1
Somewhat Helpful – 1
Helpful – 13
Very Helpful – 0
Are you comfortable using the software?
Not comfortable – 0
Somewhat comfortable – 3
Comfortable – 7
Very comfortable – 5
Did software suggest additional testing beyond your recommendation?
Yes – 6
No – 9
Did software recommend an inappropriate test?
Yes – 0
No – 15
Supervisor's Comments
Level of technician's experience on 3000 Chopper?
Inexperienced – 1
Somewhat Experienced – 1
Very Experienced - 13
Do you feel Software allowed more flexibility in work assignments?
Yes – 3
No – 12

Most of the technicians (13) reported that the program was helpful. This was even though 13 of the technicians were considered very experienced. It is telling, however, that only 5 of the 15 indicated that they were "very comfortable" using the software.

In discussions with technicians the reaction to the tool was mixed. Perhaps predictably, the relative acceptance was inversely proportional to the individual's experience. There were some exceptions to this in that there were some very experienced technicians who felt strongly that the concept of an AI diagnostic tool coupled to on-line documentation is a worthwhile endeavor.

It should also be noted that, without exception, the reaction of the less experienced workers was very positive. This is very important, as these are the workers who will benefit most from application of the tool. Further, these are the individuals who will be tomorrow's experienced technicians and will have "grown up" using the tool. Through attrition of senior technicians, the "diagnostic assistant" will gain wider acceptance.

Many of the more experienced technicians expressed a lack of confidence in the tool. Some verbalized the concern that the AI tool represented a threat to their job security.

One of the questions of the critique was meant to gauge flexibility in work assignments because of the tool. However, most tests were performed by experienced technicians and therefore the supervisors did not see how a diagnostic tool was going to provide any more flexibility. A better evaluation of workload flexibility would be achieved if all propulsion failures were analyzed using the "diagnostic assistant" and more complex staffing decisions were present.

An attempt was made to develop an estimate of diagnostic time for each of the seven models based on historical data. The objective was to compare these estimates with actual diagnostic time using the "diagnostic assistant." However, this proved problematic as there is no differentiation between actual diagnostic and total maintenance time in the historical data. WMATA was hesitant to provide an estimate of an average diagnostic time due to the highly subjective nature of this information.

Overall, WMATA management is very supportive of the use of the "diagnostic assistant." Further refinement and use of the tool will be discussed within WMATA.

CHAPTER III

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

The development and testing of the artificial intelligence (AI) diagnostic program resulted in several conclusions. The conclusions are listed below in descending order of importance.

1. The AI diagnostic program approach is feasible.
2. There appears to be the potential for cost savings in railcar maintenance using this approach.
3. The AI diagnostic program is effective in performing diagnosis and is easy to use.
4. The diagnostic program allows workload leveling.
5. Developing the diagnostic program provides valuable insight into the diagnostic process.
6. The diagnostic program can be effectively used to train technicians in diagnosis.
7. Development of the diagnostic program is fairly quick and easy.
8. There are some faults that are difficult to diagnose.
9. There is some resistance to using to the program to perform diagnosis.

This effort has shown that development and use of an AI-based "diagnostic assistant" program is feasible. Development of the program is straightforward and does not require a substantial capital investment. Correct diagnosis can be determined in an efficient manner even by maintenance technicians who do not have extensive experience in diagnosing propulsion system faults.

The use of the "diagnostic assistant" by a transit agency should save maintenance dollars, as well as increase railcar availability. Quantification of the cost savings potential could not be accomplished in this demonstration effort. To determine cost savings the diagnostic program would have to be compared with a baseline. A baseline, which would allow a direct comparison (in quantifiable terms), could not be developed. This was because the historical maintenance data combined vehicle wait, diagnosis, and repair times. Additionally, the historical data were categorized differently than the models developed for the "diagnostic assistant" program. Determination of cost savings would require tracking of the total maintenance time for propulsion system faults across an extended use of the "diagnostic assistant" in operational mode (ensuring that the program was used). Monitoring maintenance time for a full year would probably provide enough data.

Most maintenance technicians who use the program find the "diagnostic assistant" convenient and effective. This program provides personnel who are less experienced the ability to perform needed propulsion system diagnosis. The effect of this is workload leveling related to that diagnosis. Propulsion system diagnostic expertise is now available to all shifts. Additionally, diagnostic expertise is maintained in the program even when expert maintenance personnel leave or retire.

Working with maintenance technicians and managers in the knowledge engineering process allows insight into the diagnostic process. The rigors of the process provide the transit agency visibility into the current maintenance activities in a structured environment. Both technicians and managers better understand the diagnostic process and can help identify potential maintenance practice improvements. The diagnostic program also provides a valuable training tool for maintenance personnel. The program can step through and explain the diagnostic process for the specific system and allows for "what-if" scenarios.

The program is fairly easy to develop. The development and modification of the propulsion system model was accomplished in short time—slightly less than one year. The issue related to the level of detail or depth of the model was continually considered during the development, however the resulting mix of high level and detail was considered adequate. Changes to rules within the system occasionally had unexpected results. It is unclear if this was the result of the approach or particularly related to the COTS AI shell.

There are some propulsion system problems that could not be solved. They fall into two categories: (1) intermittent faults and (2) faults for which a test could not be performed. In the first category, true intermittent faults (e.g., loose electrical connection) may not be reproducible. In the second category, identification of some faults requires a test that cannot easily be performed. For example, a fault may require that the suspect railcar be operated above the maximum speed that is allowed in the maintenance area.

There are maintenance personnel who are resistant to using this advanced technology. Those who are already experts in performing diagnostics do not need to use the program. Others may be reluctant due to concern about job security or their lack of computer skills.

RECOMMENDATIONS

The effort described in this report was the initial application of the "diagnostic assistant" and was intended as a proof of concept demonstration. The recommendations are listed below in descending order.

1. Collect cost data for one year.
2. Interface the diagnostic program into the maintenance information network.
3. Use component-based maintenance reporting.
4. Expand the diagnostic program to include additional railcar systems.
5. Add event logging to railcars to capture anomalous data.
6. Add multimedia and on-line technical reference to the diagnostic program.
7. Use diagnostic program as training aid.
8. Integrate diagnostic program and on-line reference material into new railcar designs.
9. Research adapting diagnostic program as an on-board monitor.

The "diagnostic assistant" program is capable of being operationally deployed to diagnose WMATA railcar propulsion system faults. Use of the program for a year would provide the necessary data to determine cost savings as well as increased availability data for the railcars. The transit industry could use the development cost information versus the cost savings data to justify using this approach at other transit authorities.

Interfacing the diagnostic program with the maintenance information network can develop additional capability. In general, the connection may be through transferring diagnostic data via floppy disk or direct network connection. Additionally, the transit industry should use component-based maintenance reporting. This will allow tracking maintenance by various parameters such as detailed fault information, waiting time (before maintenance commences), time to diagnose, and type and time of repair. There data could also be used to update the probabilities for component failures and thereby increasing the overall maintenance efficiency.

The diagnostic program should be expanded to include other transit railcar systems. This would require developing additional models and rules appropriate to those systems. The automatic train control system and the braking system are the recommended additional systems to be included into the "diagnostic assistant" program. Additional models would have to be developed to include these systems.

It is recommended that an on-board event-logging capability be implemented for those railcars that do not already have such. This would help with the initial symptom identification. This capability is particularly important for identifying intermittent problems. The event-logging capability would capture and record parameter values out of range for a period of time (1-5 seconds is sufficient). The maintenance technician could then use this information as input to the diagnostic program.

The addition of multimedia capability to the program will help the technicians. On-line technical manuals, historical maintenance data, graphics, pictures and even video clips can be used to great effect by the technicians. If the program has direct access to the transit agency's maintenance information system through a network connection, the data can be downloaded as needed.

The "diagnostic assistant" can be used to train maintenance personnel in diagnosing propulsion systems. Additional capability could be added to the program to include sample cases of system faults, progressive tutorials, capturing of responses, and feedback. This additional capability would make the program an even more valuable teaching tool.

Procurement specifications for new railcar design could benefit from integrated diagnostic capability and on-line technical reference material. Designing this capability into the new railcars would allow for greater flexibility and ease of diagnosis, as well as other aspects of the maintenance process.

The diagnostic program could ultimately be placed on-board the railcar and used to monitor the status and condition of the railcar. It is recommended that research into this capability be performed. If an event or fault occurred, the program could record and in some cases identify the fault. Modifying the current approach is not trivial, but may be appropriate for railcars that seem to have intermittent faults. Sensors, along with an interface would have to be included on-board, along with a front-end software control program.

APPENDIX A

PROPULSION SYSTEM CHARACTERIZATION

TRACTION MOTORS

The traction motors used in the WMATA cars series 3000 are either Westinghouse type 1462B or 1462-BA motors. Each vehicle is equipped with four such motors, one per axle. Two types are identical except for internal configuration of the commutator. They are mechanically and electrically interchangeable. Set of two traction motors mounted on tracks are shown on Figure A-1.

The 1426B motor is a four-pole, direct current commutation pole, self-ventilated, series wound traction motor. It is designed to operate from 350 V; in WMATA cars there are two in series from a 700 V line. Each motor has 170 hp and can develop up to 5400 rpm. The gear unit provides a 5.414:1 reduction in motor speed to axle speed.

CURRENT TRANSDUCERS

The propulsion control logic must provide signals to the chopper in order to provide the tractive effort as requested by train operator. Important components in this control loop are the motor currents and line current. Signals representing these variables are provided by the transducers TD1, TD2, TD3 and TDR.

These transducers use the Hall effect to produce an output signal proportional to the motor current. The Hall effect occurs when the charge carriers moving through a material experience a deflection because of an applied magnetic field. This deflection results in measurable potential difference across the side of the material which is transverse to the magnetic field and the current direction.

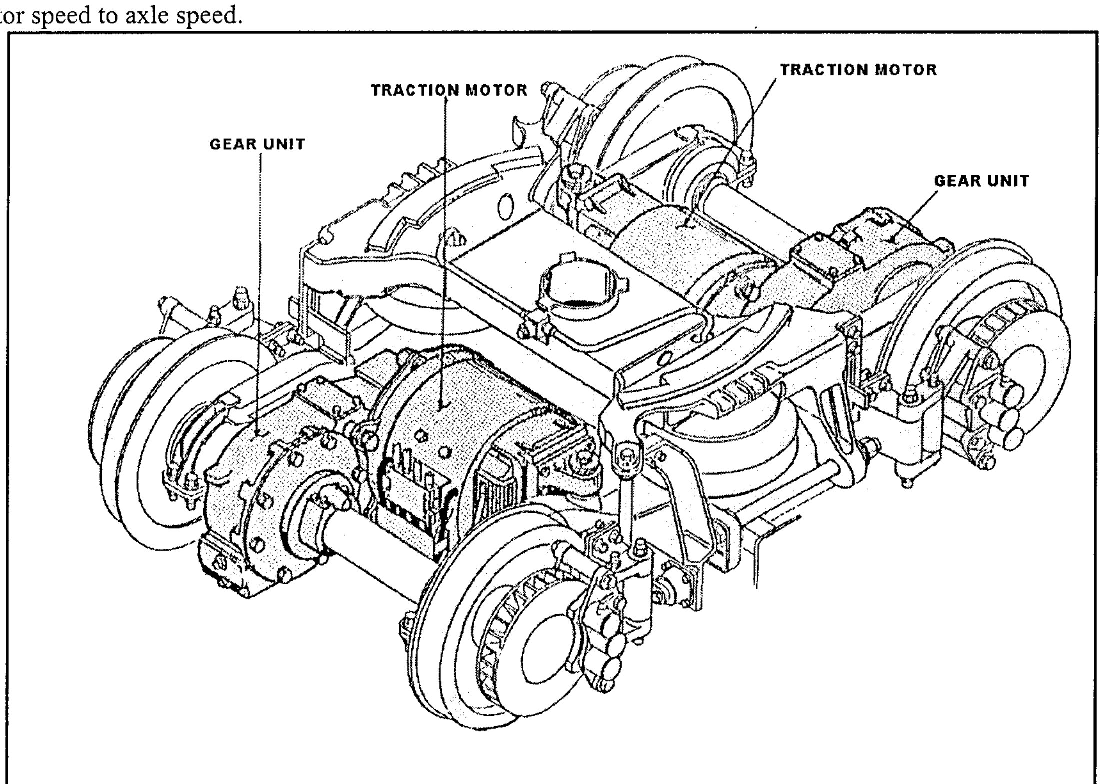


Figure A-1. Traction Motors.

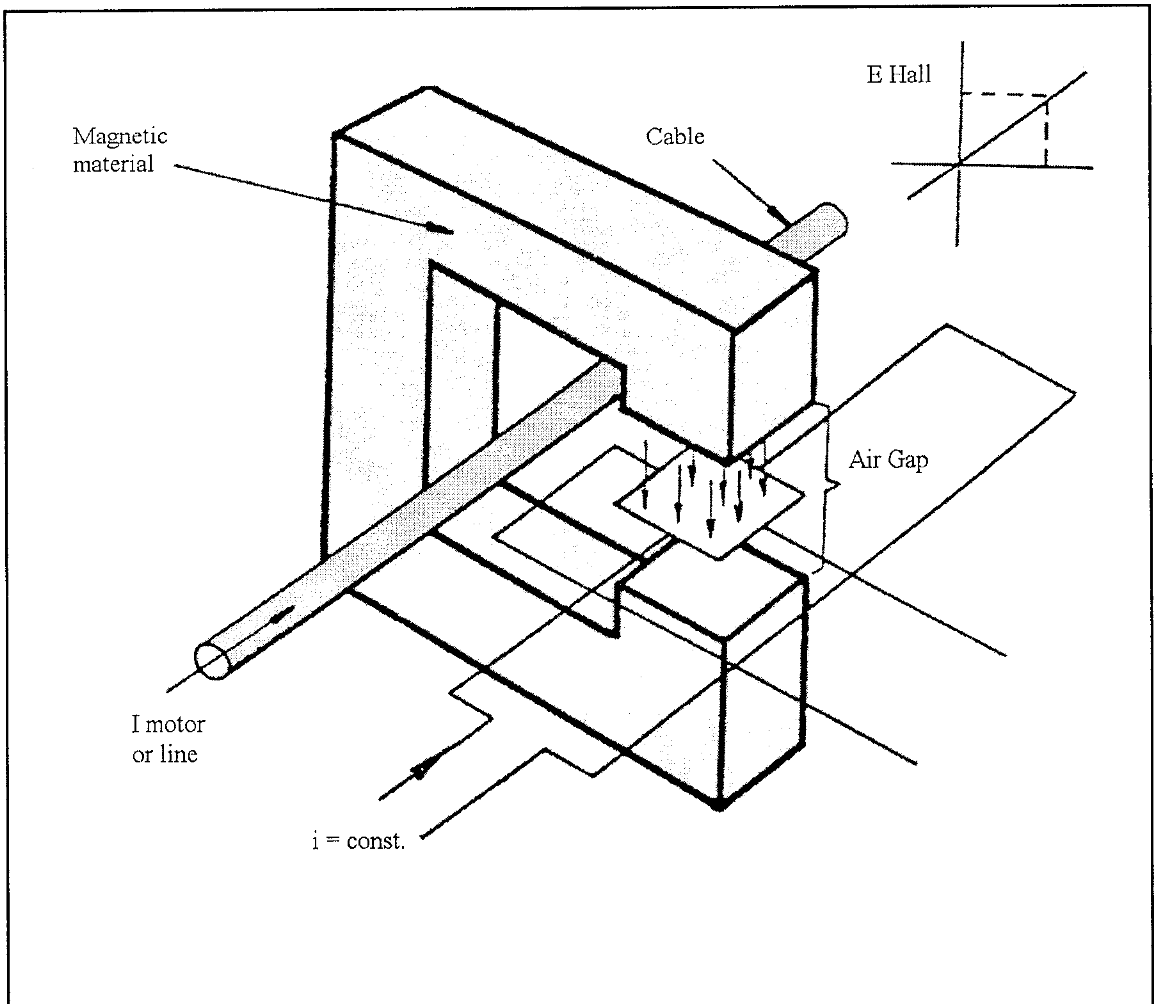


Figure A-2. Hall Effect Principle

The Hall effect principle is shown at Figure A-2. The output from transducers installed in series 3000 cars is a voltage from 0 to 10 Vdc that represent current from 0 to 2000 A. The polarity of the signal (positive or negative) shows the direction of current flow.

OVERLOAD RELAYS AND COUNTER MECHANISM

The relay is an electromagnetic device that has a coil made of wire. When current is passed through the coil, it becomes a strong magnet. Mounted on a plastic carrier, the contacts of the relay are electrically isolated from each other. The plastic carrier is connected to a piece of metal called an armature, which is drawn into the coil's center where it becomes an electromagnet. The movement of the armature causes a normally open set of contacts to move to the closed position, or set of normally closed contacts to move to the open position. After the relay is moved, it stays latched until it is released. The term normal for relays means the position where the contacts are when no power is applied to the coil. On the WMATA cars series 3000, the relays are made by Westinghouse and they are shown on Figure A-3. There are four types and only difference is in number of relays mounted on panel.

The latch can be released by energizing the reset coil. This, moves the reset armature roller away from the latch, allowing the main relay armature to return to the open position.

The Overload Relay (OLR) carries the current from the main line into the motors. This relay is adjusted to latch at about 1800 A. This will prevent damage of semiconductor box components or DC motors from incoming current rush.

The Brake Overload Relay (BOLR) is connected in series with the brake resistor. This relay pass current only in braking operation and serve the some purpose as OLR in power. It is also set to latch at 1800 A.

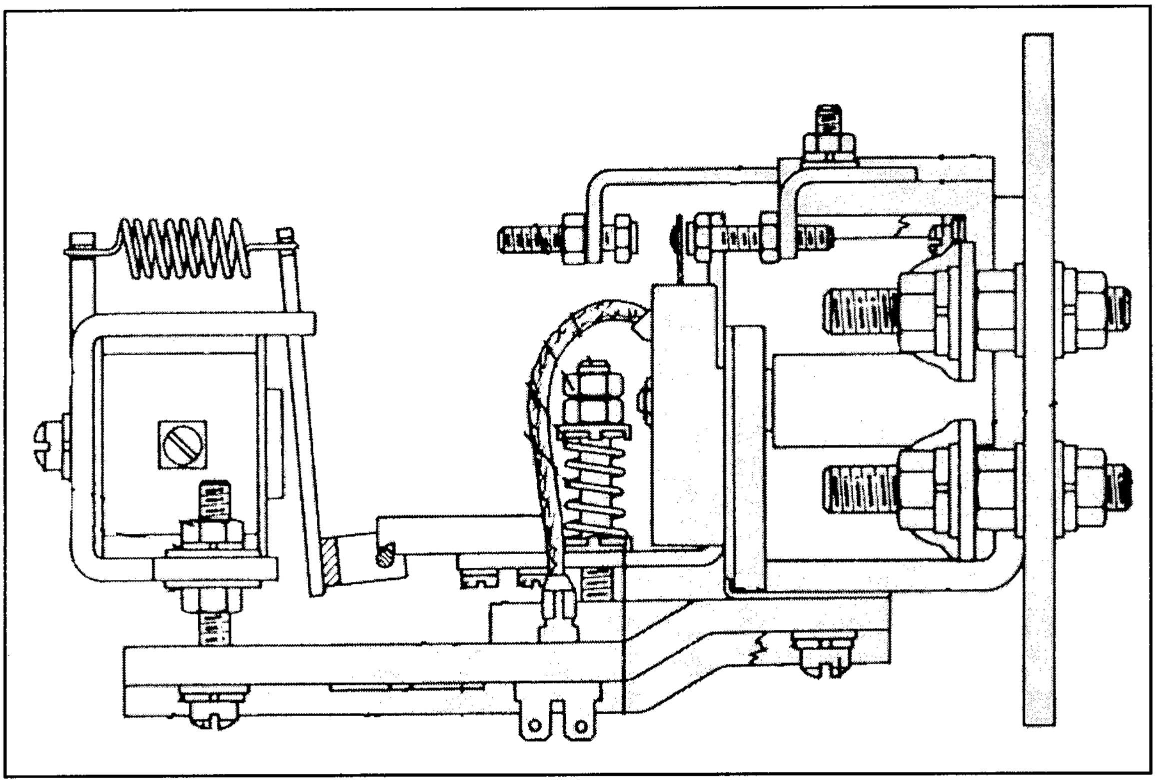


Figure A-3. Relay UT-174

The Ground Overload Relay (GDR) is latched when input current and the return currents, as measured by TD3 and TDR transducers, differ by 112 A or more. This will indicate that current is leaking somewhere out of system.

When one of the relays is tripped, the associate contact closes and the current path becomes open. The contact can be released by energizing the reset coil. This will allow the relay to return to the open position. This can be done by car operator by pressing reset button on driver's console.

The Overload Counter counts and display reset operations permitting the Operator to make a maximum of three reset operations before the counter must be reset at the Motor Control Box. This has to be done in maintenance shop by maintenance technician who will also inspect car for cause of relay latching.

SEMICONDUCTOR EQUIPMENT

The semiconductor equipment is resided in Semiconductor Box and it is consisting of thyristors, diodes, capacitors, resistors, and few other components.

Design of semiconductor equipment on 3000 series cars in modular. That means few components with similar purpose are housed in a single assembly. They are called heatsink modules. There are eleven semiconductor heat sink modules: four T1/D1, two T2/D2, one FWD/FWD, two T5/D5, one T6/D6, and one D3/D7 module. These modules are designed in such a way to prevent connecting a module in wrong location.

T1/D1 Module. Each module contains a T1 thyristor (the main chopper thyristor), a D1 diode (antiparallel) and a snubber circuit used for reduction of rush current on the thyristor. The purpose of T1 thyristor is to switch on every 3.66 milliseconds at the beginning of each logic cycle (273 Hz) thus allowing line voltage to access Motor Reactor and consequently DC motors.

T2/D2 Module. Each module contains a T2 thyristor (the main chopper turn-off thyristor), a D2 diode (antiparallel) and a snubber circuit. The purpose of T2 thyristor is to turn on at the end of chopper cycle causing T1 to go off and as a result turning off line voltage on DC motors. The turning rate of T2 depends of requested signal from train operator.

FWD/FWD Module. This module contains two free wheeling diodes connected in parallel. They curry the motor current whenever the T1 thyristor is off, and they are used to break incoming current from line to motors.

T5/D5 Module. Each module contains a T5 thyristor, a D5 diode, and a snubber circuit. The T5 thyristors will switch on only in braking mode with frequency depending of filter capacitor voltage, e.g. how much energy can be sent back to system.

T6/D6 Module. This module contains a T6 thyristor, a D6 diode, and a snubber circuit. This thyristor turns on every 3.66 millisecond (273 Hz) this stops energy from returning back to system until T5 in switched on again.

CONTROL LOGIC

As a part of the propulsion system, the Control Logic assembly continuously monitors and controls the performance of the system so that tractive effort provided by the motors matches the tractive effort requested by the train operator in a smooth, efficient and save fashion. In order to achieve this, the Control Logic execute the following functions:

Interpret the operator commands and together with information about line voltage, car speed and load, generate a tractive effort signal. This effort has to be similar to effort generates in older type of cars (CAM) because these two cars can be packed together in composition. Provides speed adjustment to provide smooth, jerk free system operation.

Provides the firing pulses to the thyristor circuits. These pulses have to set by comparing the actual current with requested current.

Provides protection against abnormal conditions such as unbalanced currents, overcurrent, overspeed, ground faults, out of tolerance line voltage. Some conditions are automatically recoverable, others required manual resetting.

The Control Logic is contained of six printed circuit boards which are positioned into slots on the motherboard. Each of the six boards performs a basic logic functions.

The Digital Input board processes digital inputs and provides power to logic assembly. Digital inputs are mostly feedback signals from various propulsion control devices. The power supply is DC to DC step down converter which provides 41 Watts of power to whole Control Logic. The Digital Output board provides digital outputs powerful enough to drive contactors in propulsion circuitry. These signals can drive relays and contactor coils up to 80 W. There are 24 outputs controlled by this board. The Analog Output board provides number of analog outputs. Among them thyristor T1/T2 and T5 firing pulses, dynamic brake feedback signal. The Central Processing Unit (CPU) contains Motorola's 8086 microprocessor which run on 5 MHz clock and 16 k RAM and 64 k EPROM memory. In memory is store software which control operation of inputs and outputs. The Analog Inputs board provides analog inputs to the computer.

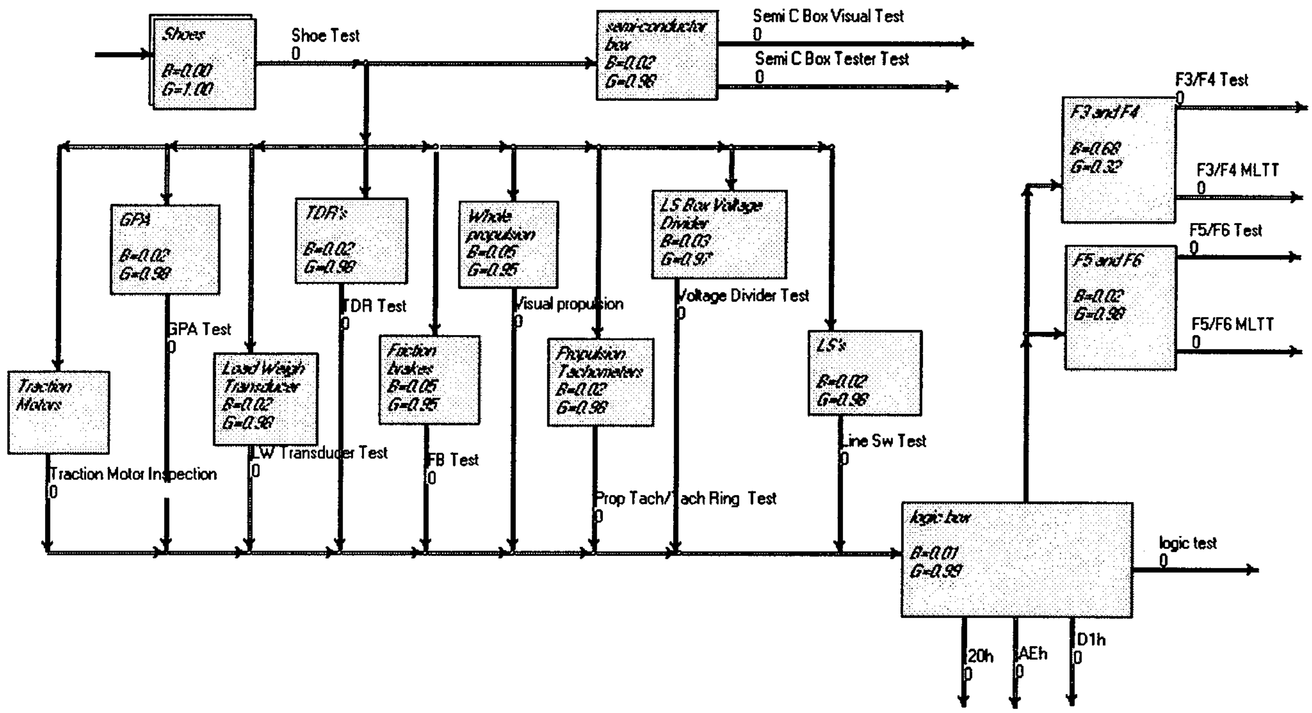
The Control Logic is located under a seat in passenger area of car. It measures approximately 50 cm by 25 cm by 20 cm and weight 13 kg. The whole Control Logic assembly is easily removable and this makes it one of the fastest troubleshooting procedures.

APPENDIX B

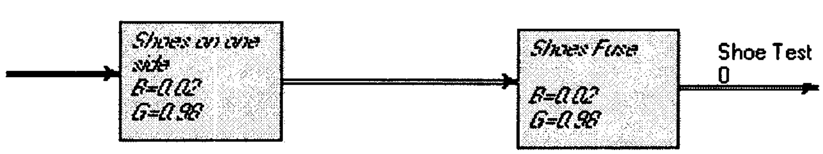
MODELS

JERKING IN PROPULSION

Jerking in Propulsion

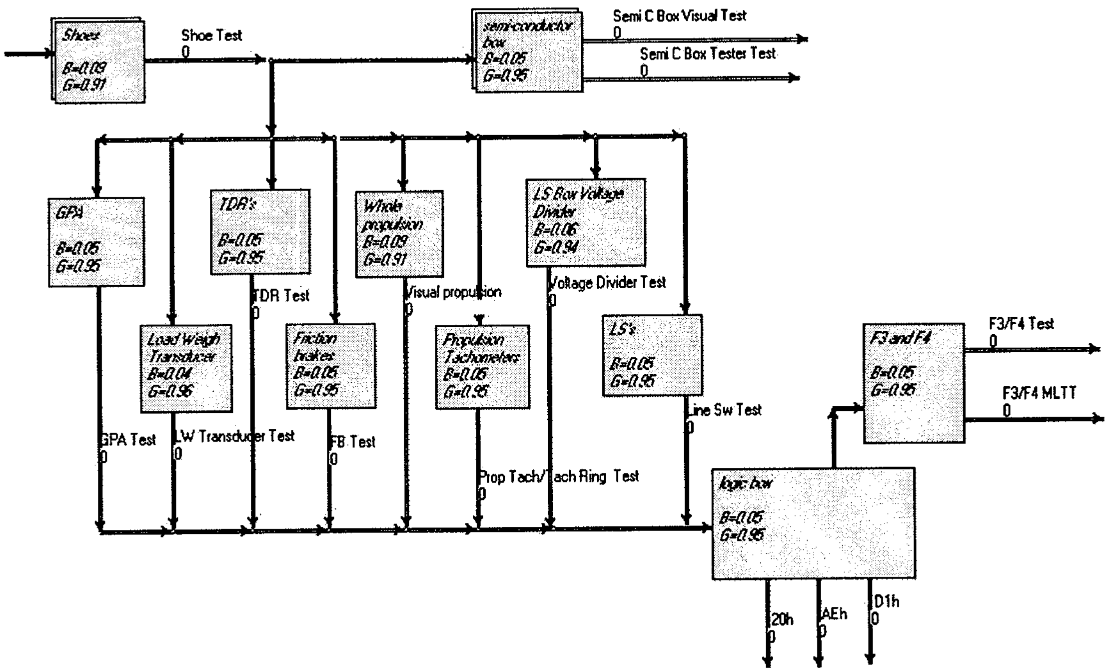


Shoes



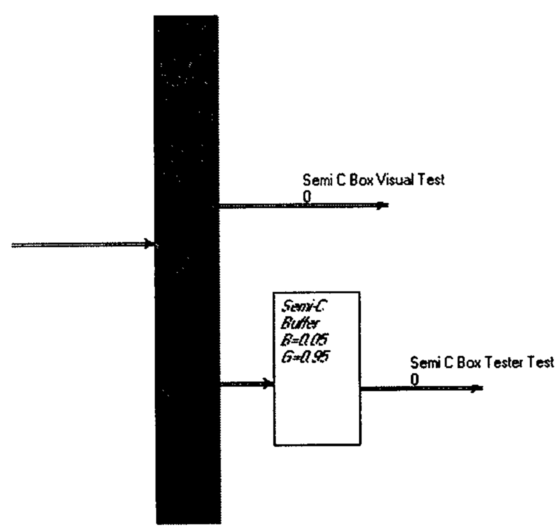
JERKING IN BRAKING

Jerking in Braking

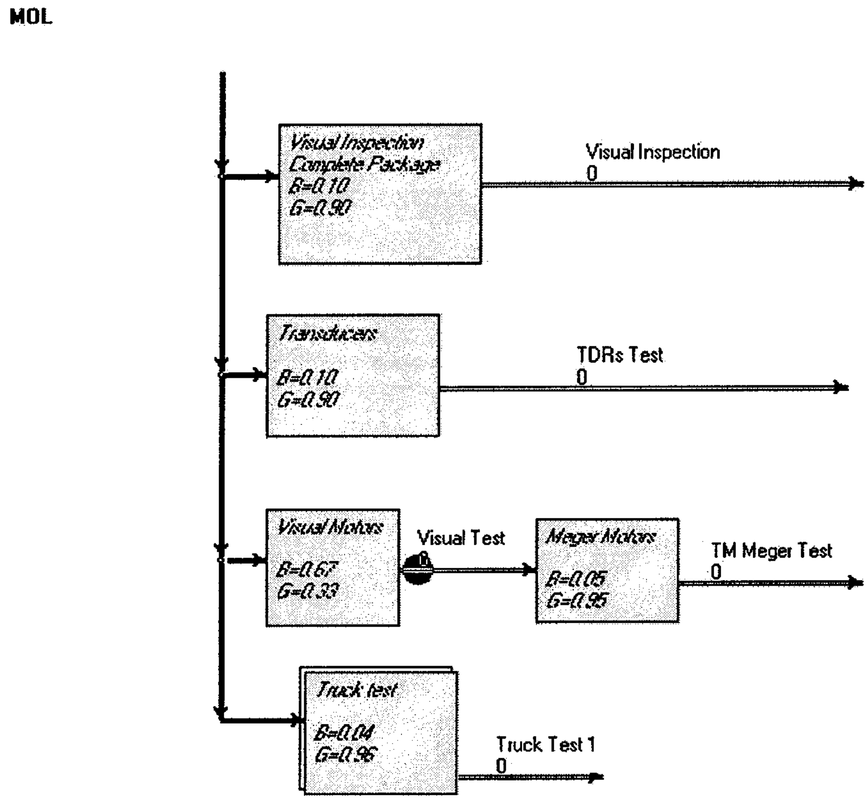


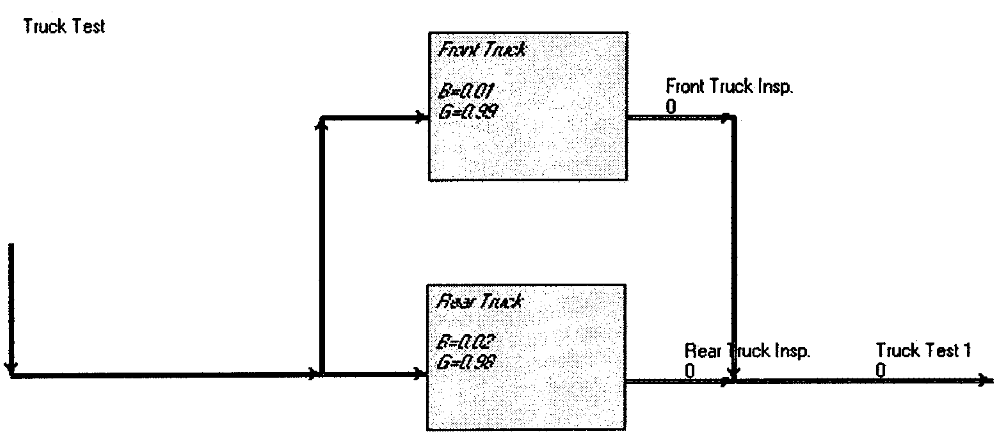
Shoes

semi-conductor box

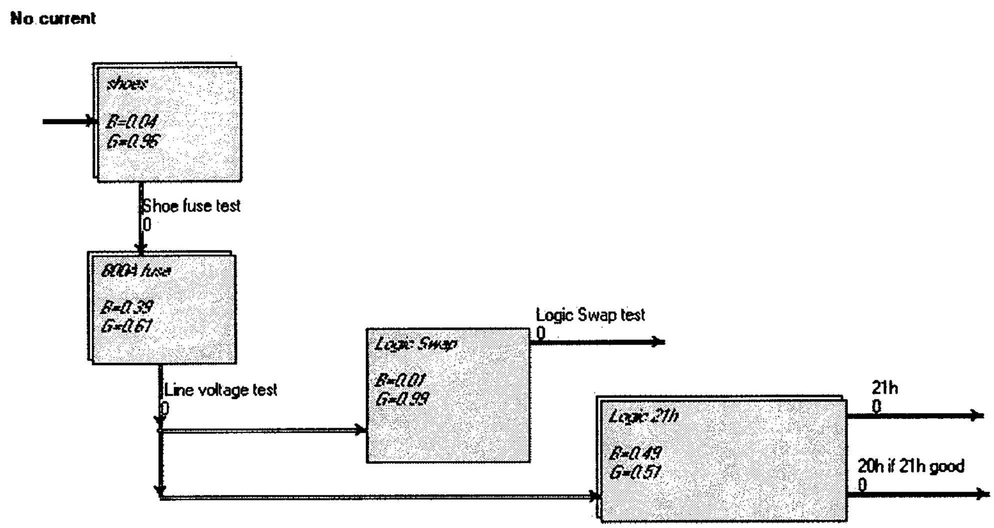


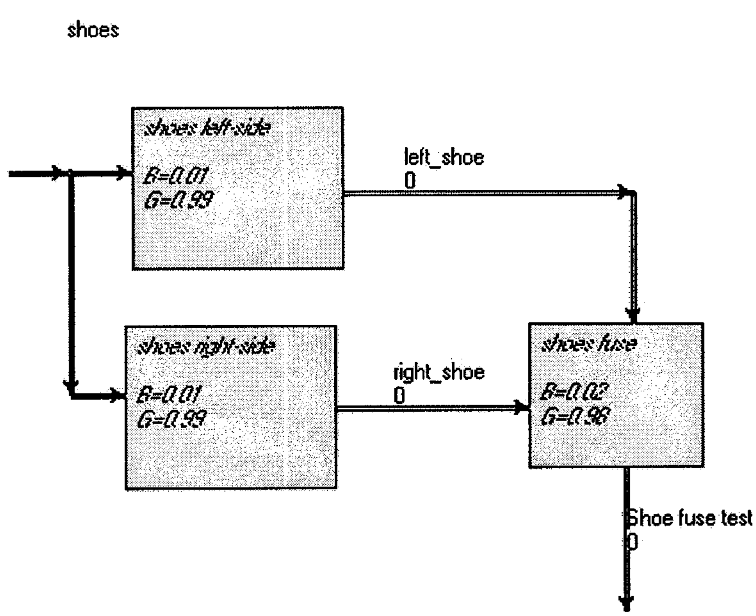
MOL


MOL
Visual Inspection
Complete Package
B=0.10
G=0.90
Visual Inspection
0
Transducers
B=0.10
G=0.90
TDRs Test
0
Visual Motors
B=0.67
G=0.33
Visual Test
0
Meger Motors
B=0.05
G=0.95
TM Meger Test
0
Truck test
B=0.04
G=0.96
Truck Test 1
0

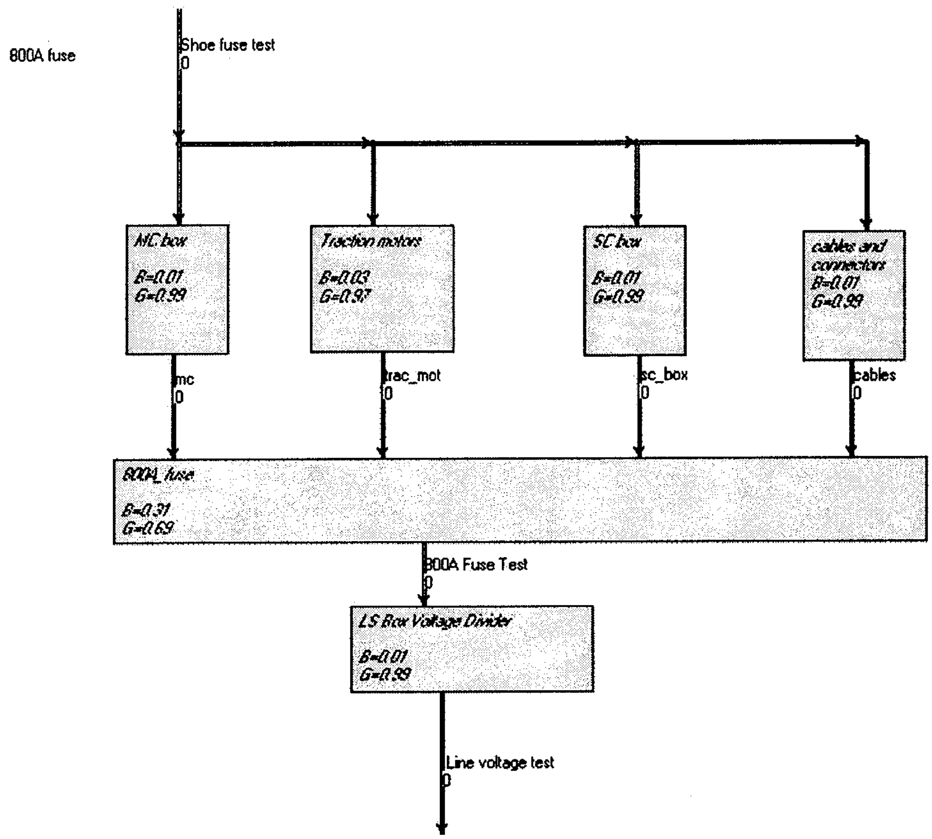

Truck Test
Front Truck
B=0.01
G=0.99
Front Truck Insp.
0
Rear Truck
B=0.02
G=0.98
Rear Truck Insp.
0
Truck Test 1
0

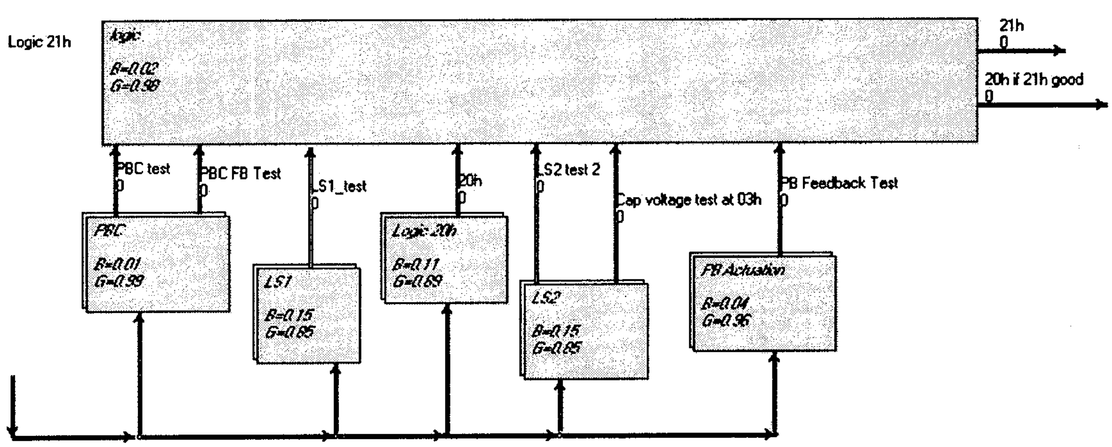
NO OR LOW CURRENT



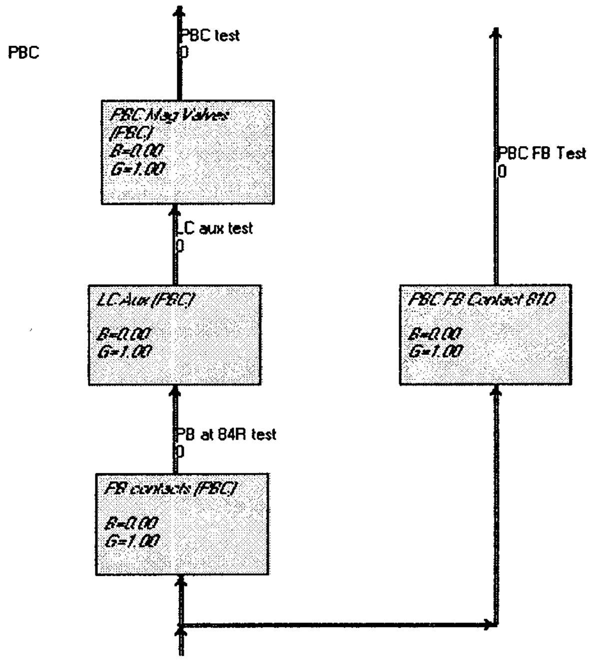


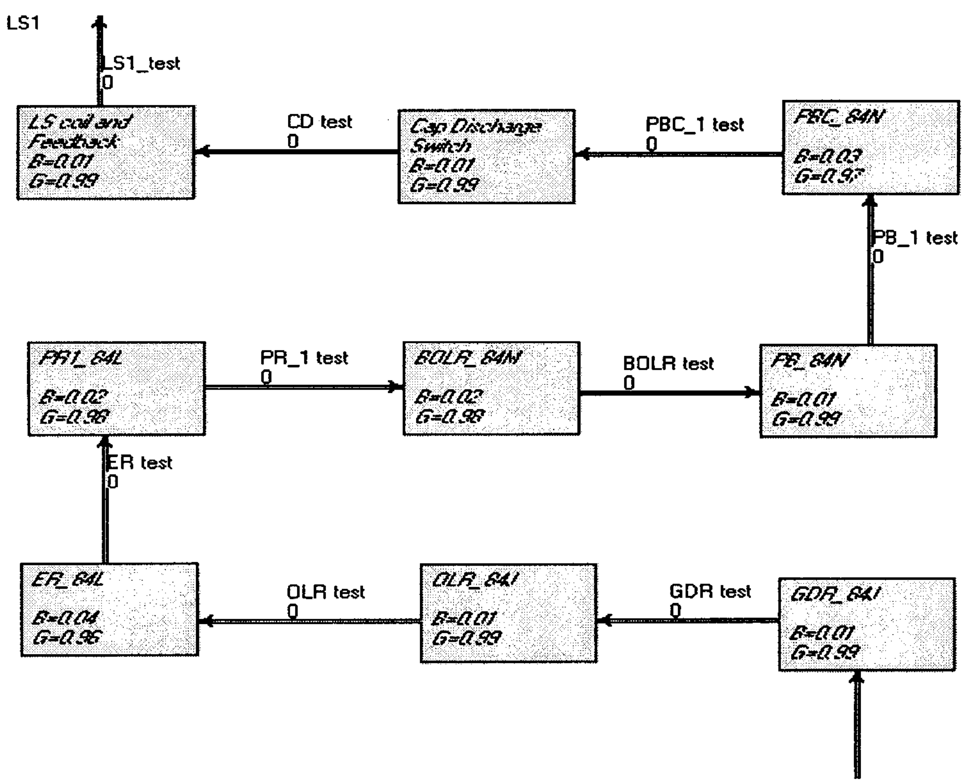
NO OR LOW CURRENT (CONTINUED)



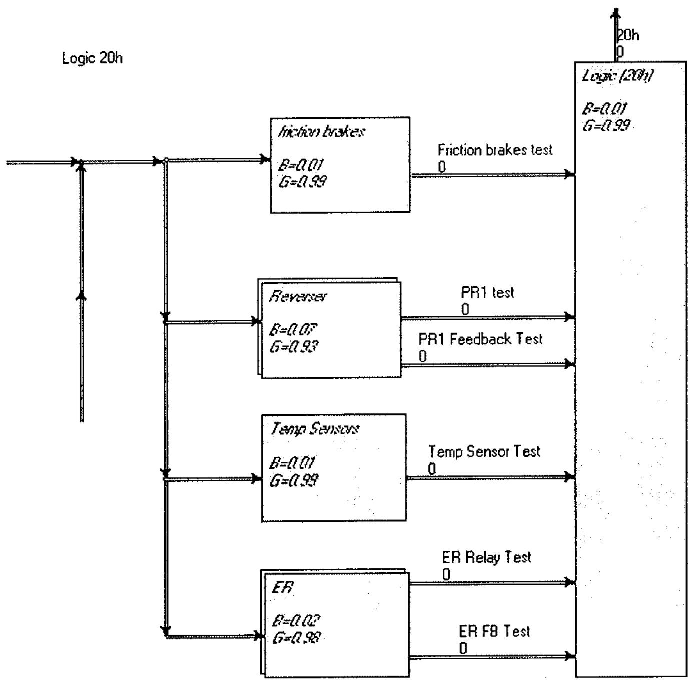


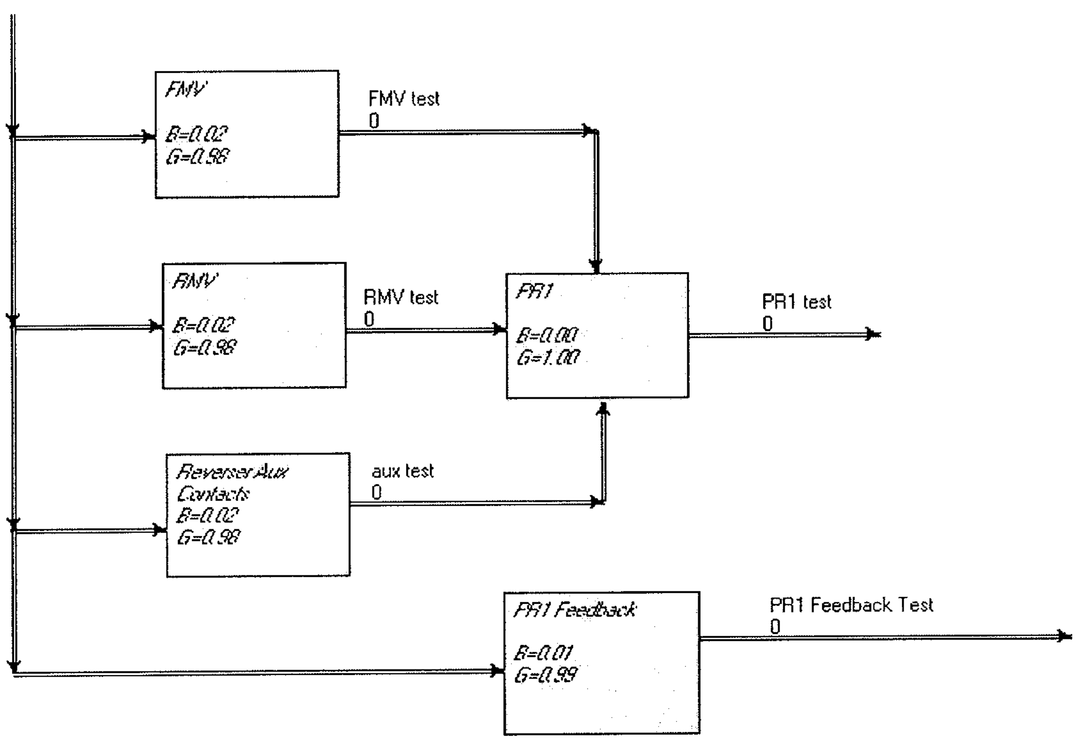
NO OR LOW CURRENT (CONTINUED)



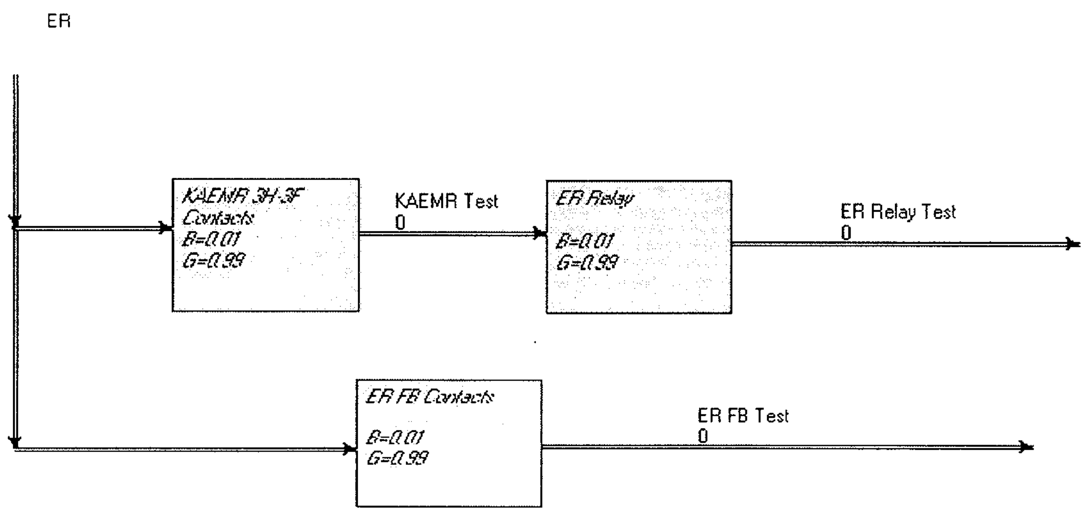


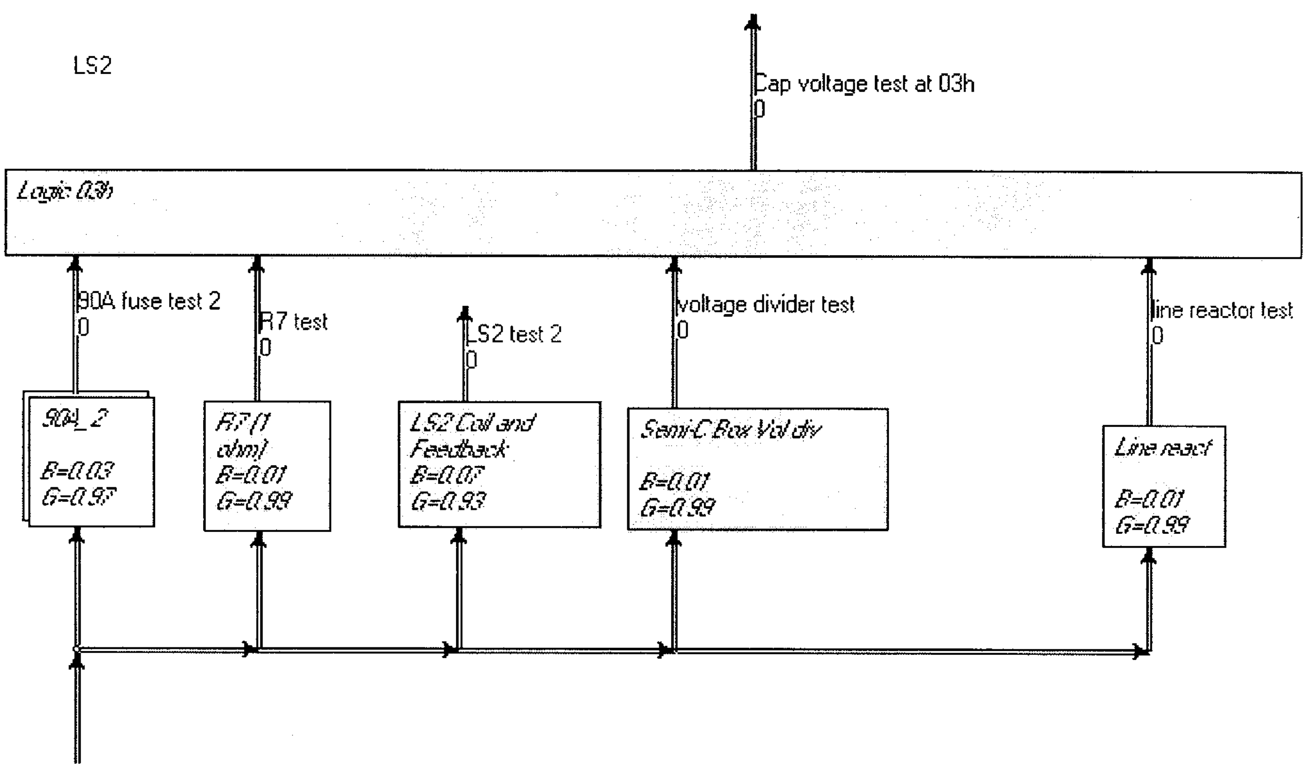
NO OR LOW CURRENT (CONTINUED)



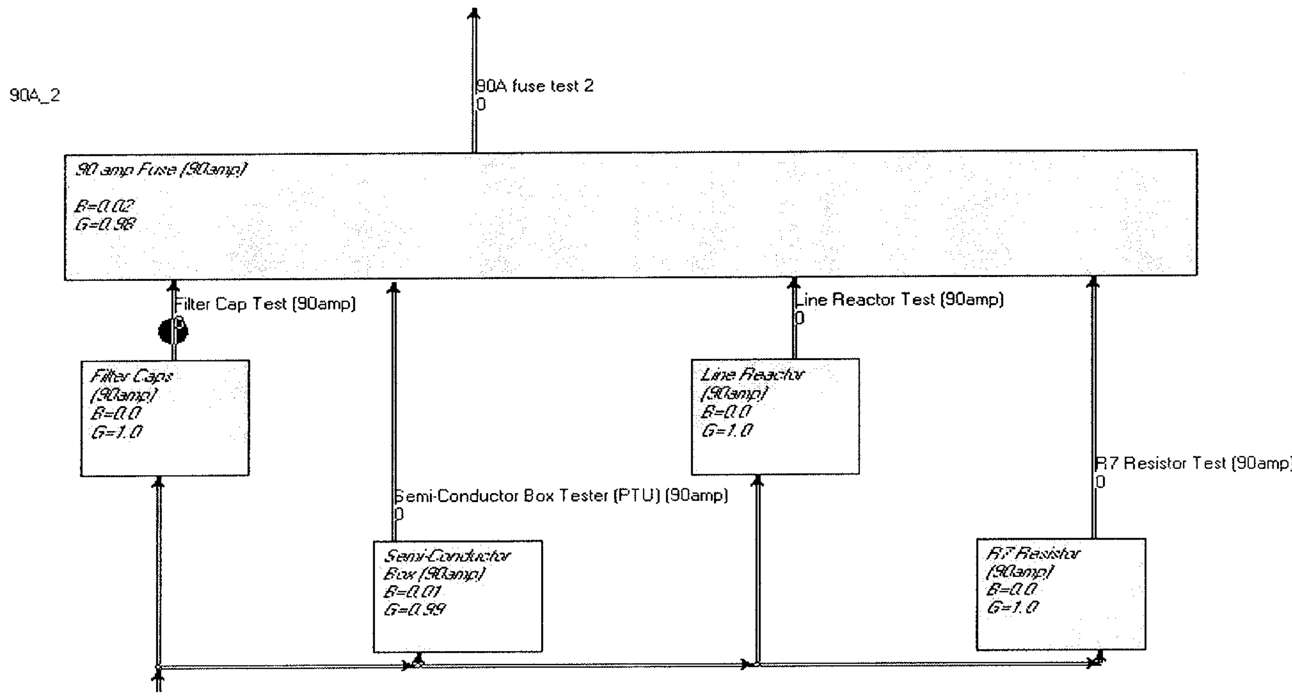


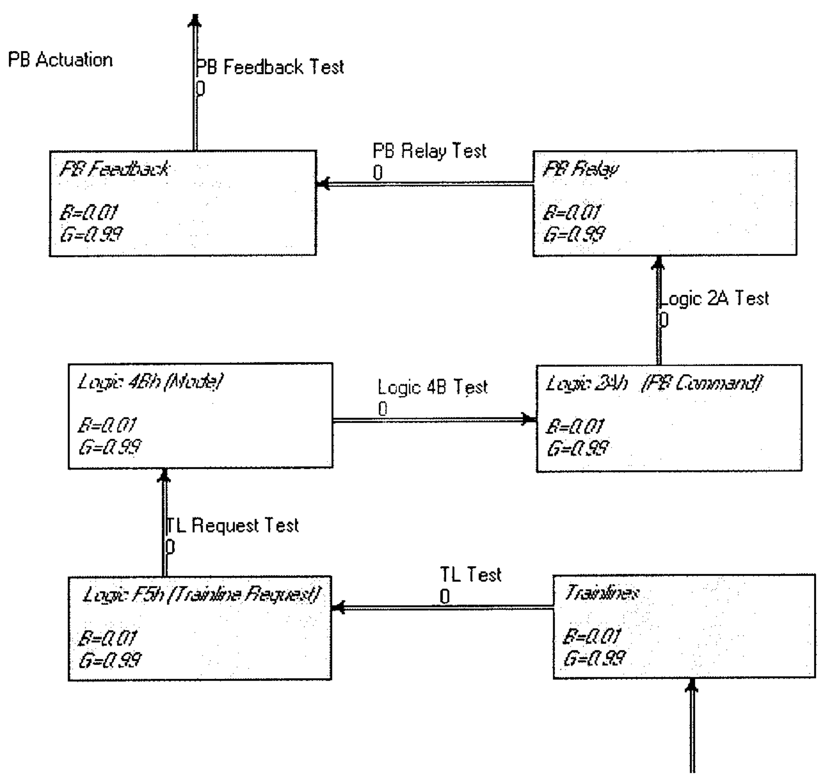
NO OR LOW CURRENT (CONTINUED)



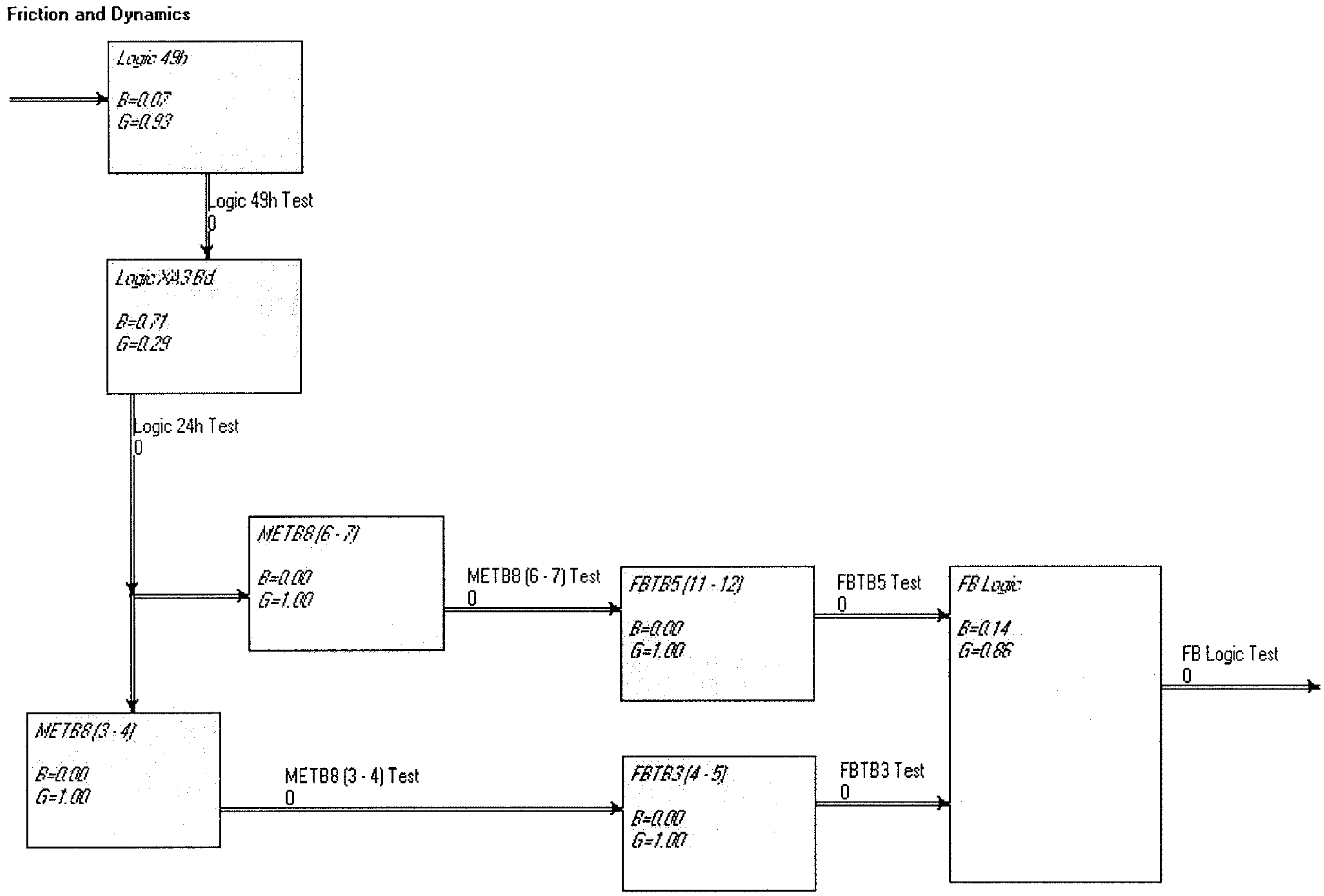


NO OR LOW CURRENT (CONTINUED)

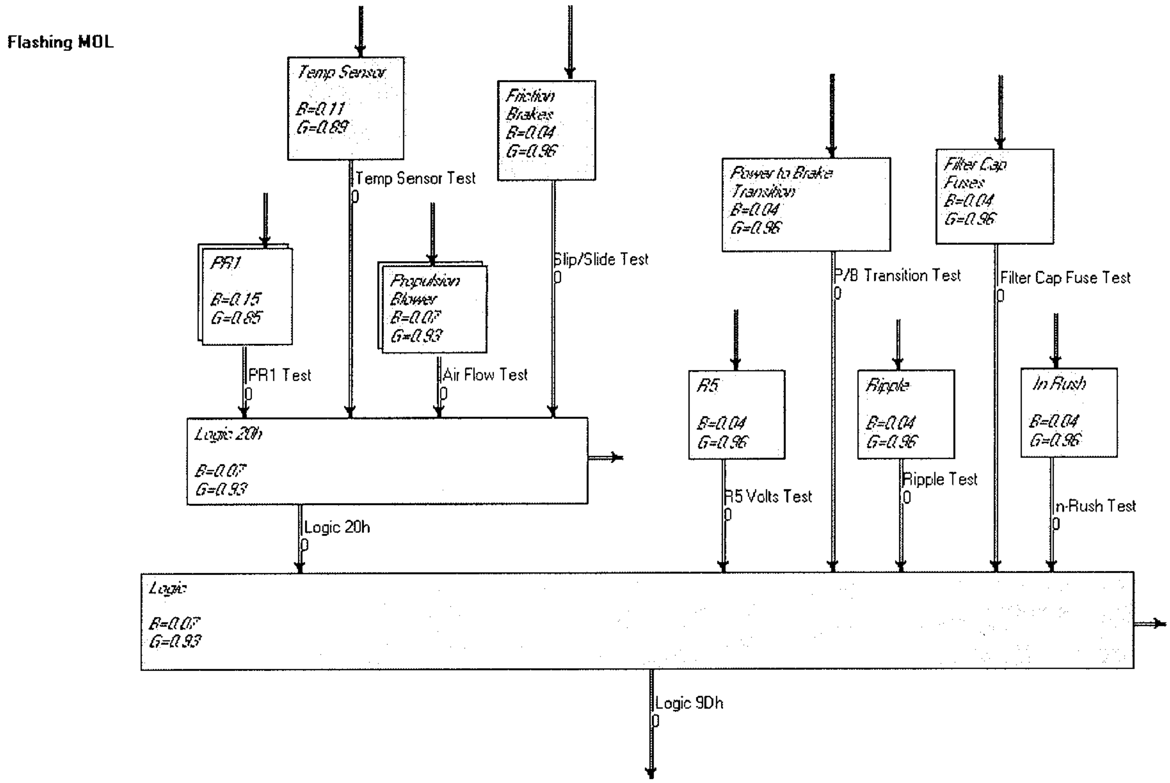


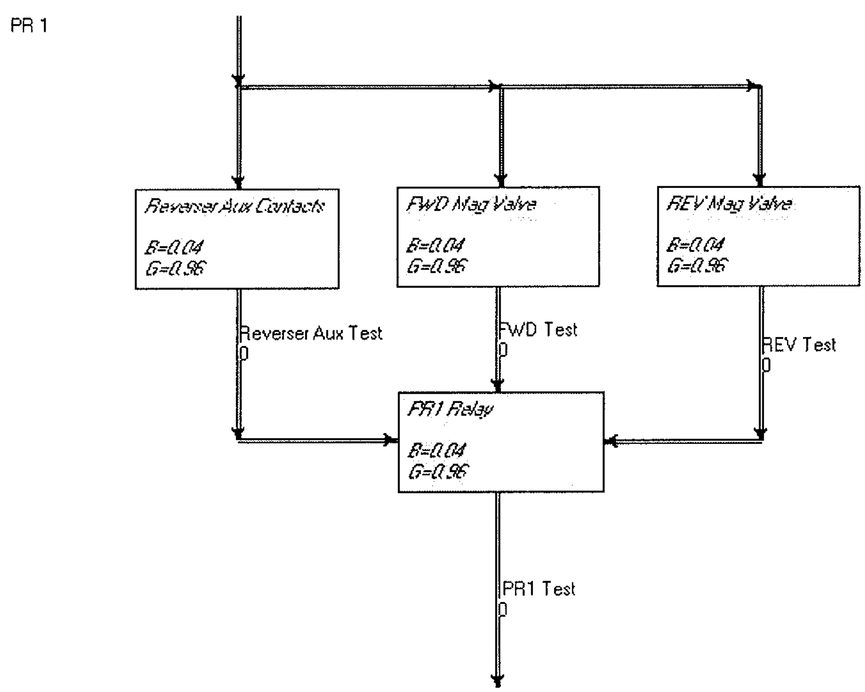


FRICTION AND DYNAMICS

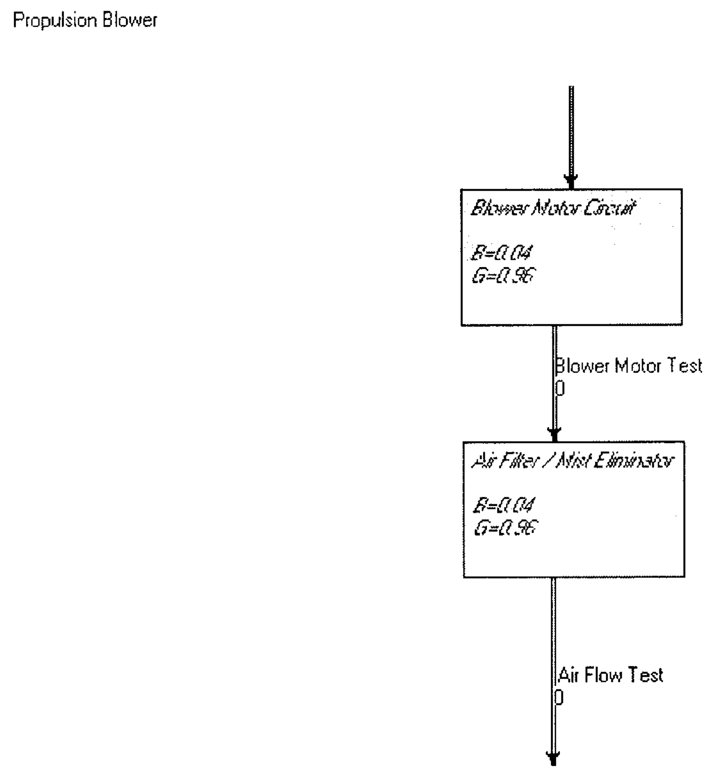


FLASHING MOL

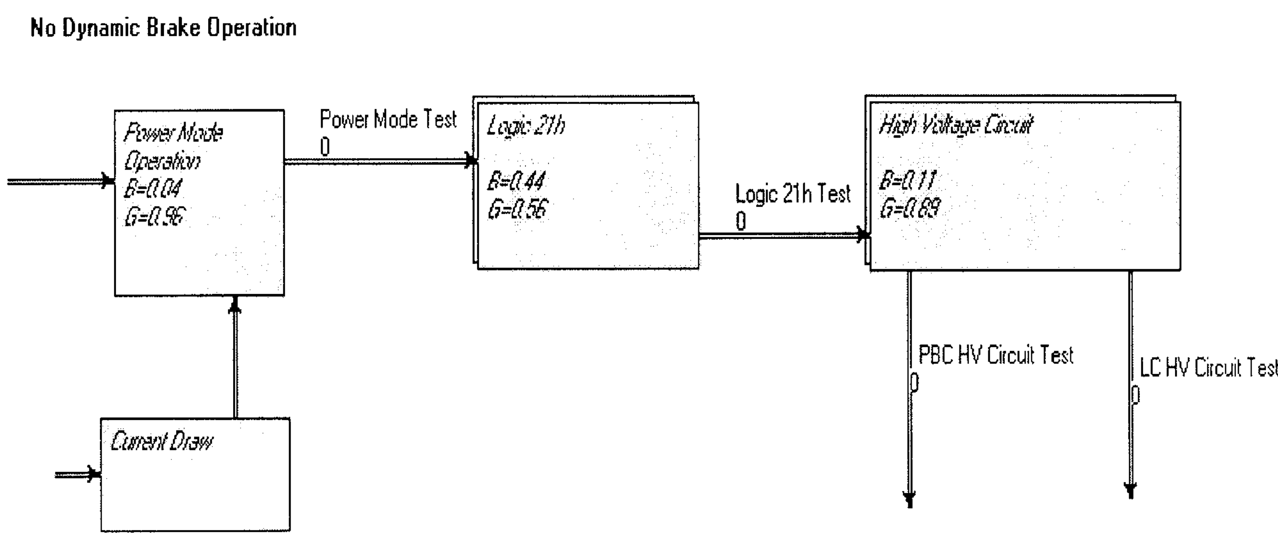




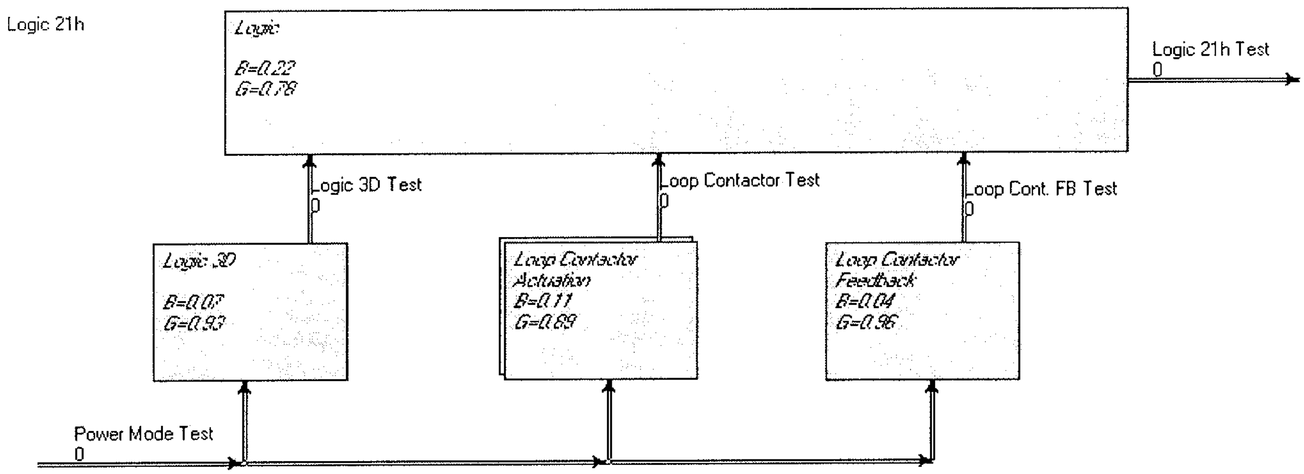
FLASHING MOL (CONTINUED)

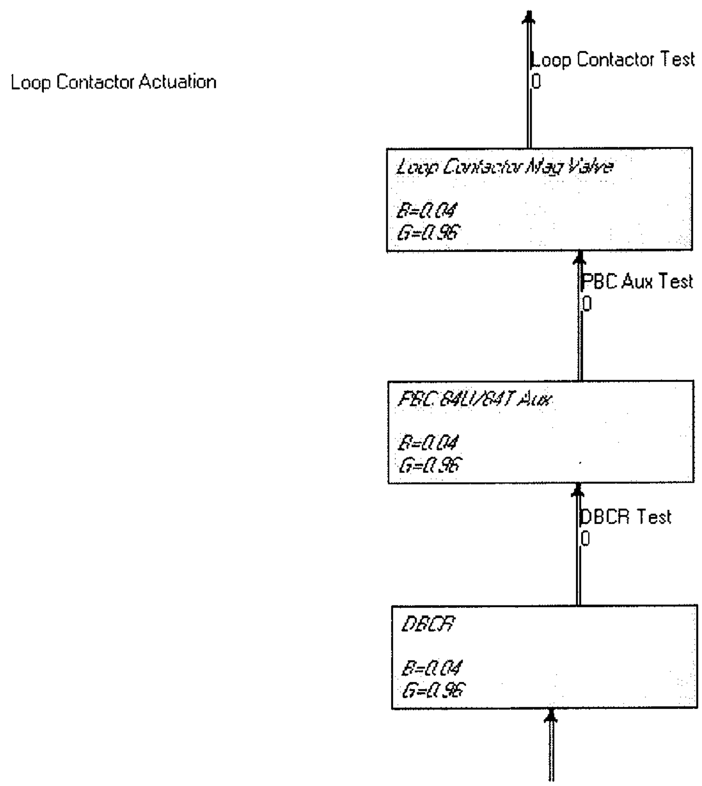


NO DYNAMIC BRAKING

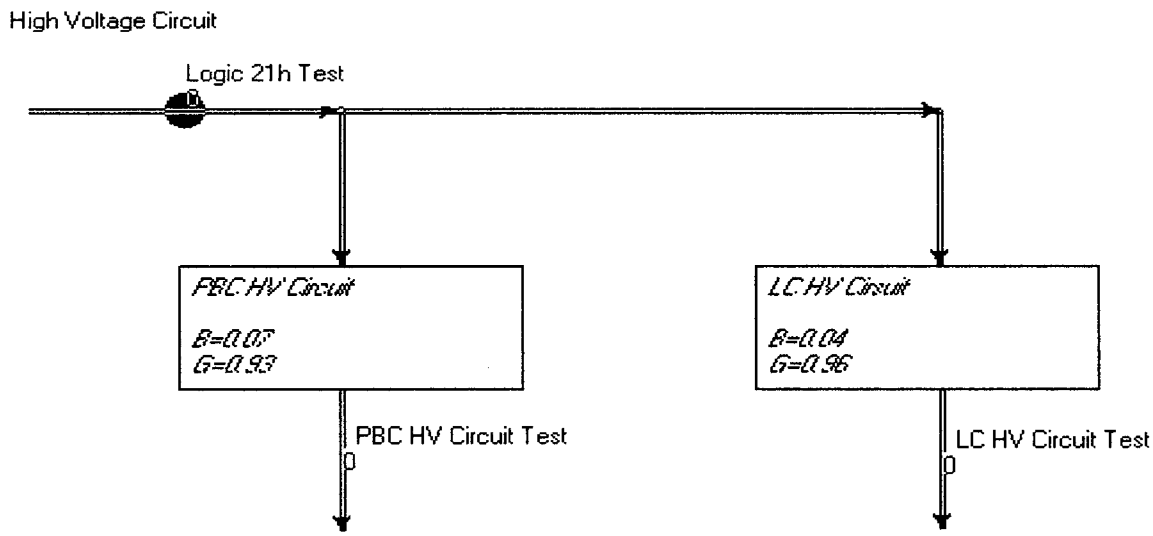


NO DYNAMIC BRAKING (CONTINUED)





NO DYNAMIC BRAKING (CONTINUED)



APPENDIX C

RULES

NO OR LOW CURRENT

```
(store-dimensions '("Blowing air" visual voltage "logic code" ohm Operational))
(store-preconditions
 '("Check if air is blowing" "Look at 21h, 87=good"
                  "84=bad"
                  "85=bad"
                  "80=bad"
                  "00=bad"
                  "check for 37V at MCJ1-R "
                  "measure line voltage"
                  "check shoes and shoe fuses"
                  "ohm meter R8 test"
                  "ohm meter 15A fuse"
                  "check for 37V at MCJ1-T"
                  "check for 37V at MCJ1-G"
                  "Look at 20h.  3E = Good"
                  "32h=bad"
                  "look at 67h, 67=01 bad"
                  "20h=3e good"
                  "look at 0Ch"
                  "look at 03h, Good if between 94h and C0h"
                  "good if over 7Bh"
                  "Test LS 2 Mag valve and Feedback contacts."
                  "Test LS 1 Mag valve and Feedback contacts."
                  "Check for 37V at MCJ1-Y."
                  "Check for 37V at MITB1-3."
                  "Check for 37V at MCJ1-V."
                  "If reads 3A, confirm failure in both directions"
                  "Look at 0Eh, should read between A6 and C0."
                  "Inspect TM's for flashing"
                  "Inspect MC Box for flashing or loose connections."
                  "Inspect cables for flashing or loose connections."
                  "Inspect Semi-C Box for flashing or loose connections."
                  "Key-up train and listen for HVAC operation."
                  "Remove LS Box cover and perform ohm check of 90A fuse."
                  "Perform ohm and visual check of Line Reactor."
                  "Test LS1s operation and HV circuitry for continuity."
                  "Test LS2s operation and HV circuitry for continuity."
                  "Inspect Right Collector Shoes for good connection."
                  "Inspect Left Collector Shoes for good connection."
                  "Perform ohm test of 800A main fuse."
                  "Perform visual and ohm test of R7 1 ohm resistor."
                  "Inspect LS Box Voltage Divider and circuitry."
```

```
                    "Inspect Semi-C Box Voltage Divider and circuitry "
                    "Inspect PB for proper mounting and operation."
                    "Check for 37v at MCJ1-d"
                    "Inspect PR1 for proper operation."
                    "Perform ops test of FMV."
                    "Perform ops test of RMV."
                    "Check Revser aux contacts for continuity."
                    "Check Brake Tach Sensors and Rings."
                    "Visually inspect Filter Cap banks and ohm test fuses."
                    "Perform megger test of R7 to ground."
                    "Perform megger test of the Line reactor to ground."
                    "Perform Semi-conductor box tester procedure."
                    "Look at 20h, should be 3E"
                    "Perform test of Temp Sensing Circuit."
                    "Swap Logic with other car and run new track test."
                    "Check for 37v on 84R line comming from PB"
                    "Check for 37v on 84J wire comming from GDR"
                    "Test FB Logic S/S circuit"
                    "Check for 37v at MVJ1-w (or MCTB7-8)"
                    "Check PB Relay Feedback Circuit"
                    "Read value of Logic 2Ah, should = 01 in power"
                    "Read value of Logic 4B, should = C5 in power"
                    "Read value of Logic F5. Help file correct values"
                    "Test Trainline circuitry"
                    "Check for operation of both PBC Mag Valves"
                    "Inspect PBC FB contact 81D"))
(store-cost '"Check if air is blowing" 00.1000000000)
(store-cost '"Look at 21h, 87=good" 01.5000000000)
(store-cost '"84=bad" 00.5000000000)
(store-cost '"85=bad" 00.5000000000)
(store-cost '"80=bad" 00.5000000000)
(store-cost '"00=bad" 00.5000000000)
(store-cost '"check for 37V at MCJ1-R " 00.5000000000)
(store-cost '"ohm meter R8 test" 00.5000000000)
(store-cost '"check for 37V at MCJ1-T" 00.5000000000)
(store-cost '"check for 37V at MCJ1-G" 00.2000000000)
(store-cost '"Look at 20h.  3E = Good" 03.6000000000)
(store-cost '"32h=bad" 00.5000000000)
(store-cost '"look at 67h, 67=01 bad" 03.0000000000)
(store-cost '"20h=3e good" 00.5000000000)
(store-cost '"look at 03h, Good if between 94h and C0h" 02.0000000000)
(store-cost '"good if over 7Bh" 00.5000000000)
(store-cost '"Test LS 1 Mag valve and Feedback contacts." 04.0000000000)
(store-cost '"If reads 3A, confirm failure in both directions" 02.5000000000)
(store-cost '"Look at 0Eh, should read between A6 and C0." 00.5000000000)
(store-cost '"Inspect TM's for flashing" 02.8400000000)
(store-cost '"Inspect MC Box for flashing or loose connections." 02.8500000000)
(store-cost '"Inspect cables for flashing or loose connections." 02.8600000000)
(store-cost '"Inspect Semi-C Box for flashing or loose connections." 02.8700000000)
(store-cost '"Key-up train and listen for HVAC operation." 03.0000000000)
(store-cost '"Remove LS Box cover and perform ohm check of 90A fuse." 03.5000000000)
(store-cost '"Perform ohm and visual check of Line Reactor." 03.0000000000)
(store-cost '"Test LS1s operation and HV circuitry for continuity." 03.0000000000)
(store-cost '"Test LS2s operation and HV circuitry for continuity." 03.0000000000)
(store-cost '"Perform ohm test of 800A main fuse." 02.5000000000)
(store-cost '"Perform visual and ohm test of R7 1 ohm resistor." 03.0000000000)
```

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(store-cost '"Inspect LS Box Voltage Divider and circuitry." 04.0000000000)
(store-cost '"Inspect Semi-C Box Voltage Divider and circuitry " 03.0000000000)
(store-cost '"Inspect PB for proper mounting and operation." 03.0000000000)
(store-cost '"Check for 37v at MCJ1-d" 03.0000000000)
(store-cost '"Inspect PR1 for proper operation." 00.5000000000)
(store-cost '"Check Brake Tach Sensors and Rings." 00.5000000000)
(store-cost '"Visually inspect Filter Cap banks and ohm test fuses." 03.1000000000)
(store-cost '"Perform megger test of R7 to ground." 03.2000000000)
(store-cost '"Perform megger test of the Line reactor to ground." 03.3000000000)
(store-cost '"Perform Semi-conductor box tester procedure." 05.0000000000)
(store-cost '"Look at 20h, should be 3E" 01.5500000000)
(store-cost '"Perform test of Temp Sensing Circuit." 04.0000000000)
(store-cost '"Swap Logic with other car and run new track test." 03.2000000000)
(store-cost '"Check for 37v on 84R line comming from PB" 01.5000000000)
(store-expert-rule '(testpoint "21h")
        '(dimension "logic code")
        '(preconditions "Look at 21h, 87=good")
        '(outcome (name "21h = 00")
            (causes (bad '"ER Relay" 00.0000000000)
                (bad '"KAEMR 3H-3F Contacts" 00.0000000000)
                (bad '"ER FB Contacts" 00.0000000000)
                (bad '"PB Feedback" 00.6500000000)
                (bad '"PBC FB Contact 81D" 00.0000000000)
                (bad 'logic 00.0005733300)
                (bad '"UUT:input" 00.0005733300)
                (bad '"LS coil and Feedback" 00.0000000000)
                (bad '"Cap Discharge Switch" 00.0000000000)
                (bad 'PBC_84N 00.0000000000)
                (bad 'PB_84N 00.0000000000)
                (bad 'BOLR_84M 00.0000000000)
                (bad 'PR1_84L 00.0000000000)
                (bad 'ER_84L 00.0000000000)
                (bad 'OLR_84J 00.0000000000)
                (bad 'GDR_84J 00.0000000000)
                (bad '"LS Box Voltage Divider" 00.0000000000)
                (bad '"800A_fuse" 00.0000000000)
                (bad '"MC box" 00.0000000000)
                (bad '"shoes fuse" 00.0000000000)
                (bad '"shoes left-side" 00.0000000000)
                (bad '"shoes right-side" 00.0000000000)
                (bad '"Traction motors" 00.0000000000)
                (bad '"SC box" 00.0000000000)
                (bad '"cables and connectors" 00.0000000000)
                (bad '"PBC Mag Valves (PBC)" 00.0000000000)
                (bad '"LC Aux (PBC)" 00.0000000000)
                (bad '"PB contacts (PBC)" 00.0000000000)
                (bad '"Logic (20h)" 00.0000000000)
                (bad 'PR1 00.0000000000)
                (bad 'FMV 00.0000000000)
                (bad 'RMV 00.0000000000)
                (bad '"Reverser Aux Contacts" 00.0000000000)
                (bad '"friction brakes" 00.0000000000)
                (bad '"Temp Sensors" 00.0000000000)
                (bad '"PR1 Feedback" 00.0000000000)
                (bad '"LS2 Coil and Feedback" 00.0000000000)
                (bad '"Logic 03h" 00.0000000000)
```

```
            (bad '"R7 (1 ohm)" 00.0000000000)
            (bad '"90 amp Fuse (90amp)" 00.0000000000)
            (bad '"R7 Resistor (90amp)" 00.0000000000)
            (bad '"Filter Caps (90amp)" 00.0000000000)
            (bad '"Semi-Conductor Box (90amp)" 00.0000000000)
            (bad '"Line Reactor (90amp)" 00.0000000000)
            (bad '"Line react" 00.0000000000)
            (bad '"Semi-C Box Vol div" 00.0000000000)))
'(outcome (name "21h = 04")
      (causes (bad '"ER Relay" 00.0000000000)
            (bad '"KAEMR 3H-3F Contacts" 00.0000000000)
            (bad '"ER FB Contacts" 00.0000000000)
            (bad '"UUT:input" 00.0008340300)
            (bad '"Logic 03h" 00.0000000000)
            (bad '"LS2 Coil and Feedback" 00.0000000000)
            (bad '"LS Box Voltage Divider" 00.0000000000)
            (bad '"800A_fuse" 00.0000000000)
            (bad '"cables and connectors" 00.0000000000)
            (bad '"shoes fuse" 00.0000000000)
            (bad '"shoes right-side" 00.0000000000)
            (bad '"shoes left-side" 00.0000000000)
            (bad '"SC box" 00.0000000000)
            (bad '"Traction motors" 00.0000000000)
            (bad '"MC box" 00.0000000000)
            (bad '"Semi-C Box Vol div" 00.0000000000)
            (bad '"Line react" 00.0000000000)
            (bad '"90 amp Fuse (90amp)" 00.0000000000)
            (bad '"Line Reactor (90amp)" 00.0000000000)
            (bad '"Semi-Conductor Box (90amp)" 00.0000000000)
            (bad '"Filter Caps (90amp)" 00.0000000000)
            (bad '"R7 Resistor (90amp)" 00.0000000000)
            (bad '"R7 (1 ohm)" 00.0000000000)
            (bad '"Logic (20h)" 00.0000000000)
            (bad '"PR1 Feedback" 00.0000000000)
            (bad '"LS coil and Feedback" 00.0000000000)
            (bad '"Cap Discharge Switch" 00.0000000000)
            (bad 'PB_84N 00.0000000000)
            (bad 'BOLR_84M 00.0000000000)
            (bad 'PR1_84L 00.0000000000)
            (bad 'ER_84L 00.0000000000)
            (bad 'OLR_84J 00.0000000000)
            (bad 'GDR_84J 00.0000000000)
            (bad '"Temp Sensors" 00.0000000000)
            (bad '"friction brakes" 00.0000000000)
            (bad 'PR1 00.0000000000)
            (bad '"Reverser Aux Contacts" 00.0000000000)
            (bad 'RMV 00.0000000000)
            (bad 'FMV 00.0000000000)
            (bad '"PBC Mag Valves (PBC)" 00.0000000000)
            (bad '"LC Aux (PBC)" 00.0000000000)
            (bad '"PB contacts (PBC)" 00.0000000000)
            (bad '"PB Feedback" 00.0000000000)
            (bad '"PB Relay" 00.0000000000)
            (bad '"Logic 2Ah   (PB Command)" 00.0000000000)
            (bad '"Logic 4Bh (Mode)" 00.0000000000)
            (bad '" Logic F5h (Trainline Request)"
```

```
          00.0000000000)
        (bad 'Trainlines 00.0000000000)
        (bad '"PBC FB Contact 81D" 00.6672226900)
        (bad 'PBC_84N 00.0000000000)))
'(outcome (name "21h = 80")
    (causes (bad '"PBC FB Contact 81D" 00.0000000000)
        (bad '"PB Feedback" 00.0000000000)
        (bad '"PB Relay" 00.0000000000)
        (bad '"Logic 2Ah   (PB Command)" 00.0000000000)
        (bad '"Logic 4Bh (Mode)" 00.0000000000)
        (bad '" Logic F5h (Trainline Request)"
          00.0000000000)
        (bad 'Trainlines 00.0000000000)
        (bad '"LS Box Voltage Divider" 00.0000000000)
        (bad '"800A_fuse" 00.0000000000)
        (bad '"cables and connectors" 00.0000000000)
        (bad '"shoes fuse" 00.0000000000)
        (bad '"shoes right-side" 00.0000000000)
        (bad '"shoes left-side" 00.0000000000)
        (bad '"SC box" 00.0000000000)
        (bad '"Traction motors" 00.0000000000)
        (bad '"MC box" 00.0000000000)
        (bad '"Logic 03h" 00.0000000000)
        (bad '"LS2 Coil and Feedback" 00.0000000000)
        (bad '"Semi-C Box Vol div" 00.0000000000)
        (bad '"Line react" 00.0000000000)
        (bad '"90 amp Fuse (90amp)" 00.0000000000)
        (bad '"Line Reactor (90amp)" 00.0000000000)
        (bad '"Semi-Conductor Box (90amp)" 00.0000000000)
        (bad '"Filter Caps (90amp)" 00.0000000000)
        (bad '"R7 Resistor (90amp)" 00.0000000000)
        (bad '"R7 (1 ohm)" 00.0000000000)
        (bad '"LS coil and Feedback" 00.0000000000)
        (bad '"Cap Discharge Switch" 00.0000000000)
        (bad 'PBC_84N 00.0000000000)
        (bad 'PB_84N 00.0000000000)
        (bad '"PBC Mag Valves (PBC)" 00.0502401600)
        (bad '"LC Aux (PBC)" 00.0976308100)
        (bad '"PB contacts (PBC)" 00.0976308100)
        (bad '"Logic (20h)" 00.6028818700)
        (bad 'logic 00.0976308100)))
'(outcome (name "21h = 84")
    (causes (bad '"ER Relay" 00.0000000000)
        (bad '"KAEMR 3H-3F Contacts" 00.0000000000)
        (bad '"ER FB Contacts" 00.0000000000)
        (bad '"PBC FB Contact 81D" 00.0000000000)
        (bad '"PB Feedback" 00.0000000000)
        (bad '"PB Relay" 00.0000000000)
        (bad '"Logic 2Ah   (PB Command)" 00.0000000000)
        (bad '"Logic 4Bh (Mode)" 00.0000000000)
        (bad '" Logic F5h (Trainline Request)"
          00.0000000000)
        (bad 'Trainlines 00.0000000000)
        (bad '"Line Reactor (90amp)" 00.0000000000)
        (bad '"Filter Caps (90amp)" 00.0000000000)
        (bad '"R7 Resistor (90amp)" 00.0000000000)
```

```
        (bad '"PR1 Feedback" 00.0000000000)
        (bad 'BOLR_84M 00.0000000000)
        (bad 'PR1_84L 00.0000000000)
        (bad 'ER_84L 00.0000000000)
        (bad 'OLR_84J 00.0000000000)
        (bad 'GDR_84J 00.0000000000)
        (bad '"LS Box Voltage Divider" 00.0000000000)
        (bad '"800A_fuse" 00.0000000000)
        (bad '"MC box" 00.0000000000)
        (bad '"shoes fuse" 00.0000000000)
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        (bad '"shoes right-side" 00.0000000000)
        (bad '"Traction motors" 00.0000000000)
        (bad '"SC box" 00.0000000000)
        (bad '"cables and connectors" 00.0000000000)
        (bad '"PBC Mag Valves (PBC)" 00.0000000000)
        (bad '"LC Aux (PBC)" 00.0000000000)
        (bad '"PB contacts (PBC)" 00.0000000000)
        (bad '"Logic (20h)" 00.0000000000)
        (bad 'PR1 00.0000000000)
        (bad 'FMV 00.0000000000)
        (bad 'RMV 00.0000000000)
        (bad '"Reverser Aux Contacts" 00.0000000000)
        (bad '"friction brakes" 00.0000000000)
        (bad '"Temp Sensors" 00.0000000000)
        (bad '"LS2 Coil and Feedback" 00.0000000000)
        (bad '"Logic 03h" 00.0000000000)
        (bad '"R7 (1 ohm)" 00.0000000000)
        (bad '"90 amp Fuse (90amp)" 00.0000000000)
        (bad '"Semi-Conductor Box (90amp)" 00.0000000000)
        (bad '"Line react" 00.0000000000)
        (bad '"Semi-C Box Vol div" 00.0000000000)
        (bad 'PB_84N 00.2106954500)
        (bad '"LS coil and Feedback" 00.1854119900)
        (bad '"Cap Discharge Switch" 00.2106954500)
        (bad 'PBC_84N 00.2106954500)))
'(outcome (name "21h = 85")
    (causes (bad '"ER Relay" 00.0000000000)
        (bad '"KAEMR 3H-3F Contacts" 00.0000000000)
        (bad '"ER FB Contacts" 00.0000000000)
        (bad '"PBC FB Contact 81D" 00.0000000000)
        (bad '"cables and connectors" 00.0083333300)
        (bad 'logic 00.1666666700)
        (bad '"PB Feedback" 00.0000000000)
        (bad '"PB Relay" 00.0000000000)
        (bad '"Logic 2Ah   (PB Command)" 00.0000000000)
        (bad '"Logic 4Bh (Mode)" 00.0000000000)
        (bad '" Logic F5h (Trainline Request)"
           00.0000000000)
        (bad 'Trainlines 00.0000000000)
        (bad '"LS Box Voltage Divider" 00.0000000000)
        (bad '"800A_fuse" 00.0000000000)
        (bad '"shoes fuse" 00.0000000000)
        (bad '"shoes right-side" 00.0000000000)
        (bad '"shoes left-side" 00.0000000000)
        (bad '"SC box" 00.0000000000)
```

```
                    (bad '"Traction motors" 00.0000000000)
                    (bad '"MC box" 00.0000000000)
                    (bad '"Line react" 00.0000000000)
                    (bad '"Logic (20h)" 00.0000000000)
                    (bad '"PR1 Feedback" 00.0000000000)
                    (bad '"LS coil and Feedback" 00.0000000000)
                    (bad '"Cap Discharge Switch" 00.0000000000)
                    (bad 'PBC_84N 00.0000000000)
                    (bad 'PB_84N 00.0000000000)
                    (bad 'BOLR_84M 00.0000000000)
                    (bad 'PR1_84L 00.0000000000)
                    (bad 'ER_84L 00.0000000000)
                    (bad 'OLR_84J 00.0000000000)
                    (bad 'GDR_84J 00.0000000000)
                    (bad '"Temp Sensors" 00.0000000000)
                    (bad '"friction brakes" 00.0000000000)
                    (bad 'PR1 00.0000000000)
                    (bad '"Reverser Aux Contacts" 00.0000000000)
                    (bad 'RMV 00.0000000000)
                    (bad 'FMV 00.0000000000)
                    (bad '"PBC Mag Valves (PBC)" 00.0000000000)
                    (bad '"LC Aux (PBC)" 00.0000000000)
                    (bad '"PB contacts (PBC)" 00.0000000000)
                    (bad '"Semi-C Box Vol div" 00.0083333300)
                    (bad '"90 amp Fuse (90amp)" 00.1666666700)
                    (bad '"Line Reactor (90amp)" 00.0083333300)
                    (bad '"Semi-Conductor Box (90amp)" 00.1666666700)
                    (bad '"Filter Caps (90amp)" 00.0083333300)
                    (bad '"R7 Resistor (90amp)" 00.0833333300)
                    (bad '"Logic 03h" 00.1666666700)
                    (bad '"LS2 Coil and Feedback" 00.0083333300)
                    (bad '"R7 (1 ohm)" 00.0083333300))))
(store-expert-rule '(testpoint "PB at 84R test")
          '(dimension voltage)
          '(preconditions "Check for 37v on 84R line comming from PB"))
(store-expert-rule '(testpoint "LC aux test")
          '(dimension voltage)
          '(preconditions "Check for 37v at MCJ1-d"))
(store-expert-rule '(testpoint "PBC test")
          '(dimension visual)
          '(preconditions "Check for operation of both PBC Mag Valves")
          '(cost 03.0000000000))
(store-expert-rule '(testpoint "PBC FB Test")
          '(dimension visual)
          '(preconditions "Inspect PBC FB contact 81D"))
(store-expert-rule '(testpoint "TL Test")
          '(dimension Operational)
          '(preconditions "Test Trainline circuitry"))
(store-expert-rule '(testpoint "TL Request Test")
          '(dimension "logic code")
          '(preconditions
           "Read value of Logic F5. Help file correct values"))
(store-expert-rule '(testpoint "Logic 4B Test")
          '(dimension "logic code")
          '(preconditions
           "Read value of Logic 4B, should = C5 in power"))
```

```
(store-expert-rule '(testpoint "Logic 2A Test")
        '(dimension "logic code")
        '(preconditions
         "Read value of Logic 2Ah, should = 01 in power"))
(store-expert-rule '(testpoint "PB Relay Test")
        '(dimension visual)
        '(preconditions
         "Inspect PB for proper mounting and operation."))
(store-expert-rule '(testpoint "PB Feedback Test")
        '(dimension voltage)
        '(preconditions "Check PB Relay Feedback Circuit"))
(store-expert-rule '(testpoint LS1_test)
        '(dimension voltage)
        '(preconditions "Test LS 1 Mag valve and Feedback contacts."))
(store-expert-rule '(testpoint "FMV test")
        '(dimension Operational)
        '(preconditions "Perform ops test of FMV.")
        '(outcome (causes (bad 'FMV 01.0000000000))))
(store-expert-rule '(testpoint "RMV test")
        '(dimension Operational)
        '(preconditions "Perform ops test of RMV.")
        '(outcome (causes (bad 'RMV 01.0000000000))))
(store-expert-rule '(testpoint "aux test")
        '(dimension voltage)
        '(preconditions "Check Revser aux contacts for continuity.")
        '(outcome (causes (bad '"Reverser Aux Contacts" 01.0000000000))))
(store-expert-rule '(testpoint "PR1 test")
        '(dimension Operational)
        '(preconditions "Inspect PR1 for proper operation."))
(store-expert-rule '(testpoint "Friction brakes test")
        '(dimension ohm)
        '(preconditions "Check Brake Tach Sensors and Rings.")
        '(outcome (causes (bad '"friction brakes" 01.0000000000))))
(store-expert-rule '(testpoint "Temp Sensor Test")
        '(dimension voltage)
        '(preconditions "Perform test of Temp Sensing Circuit."))
(store-expert-rule '(testpoint "GDR test")
        '(dimension voltage)
        '(preconditions "Check for 37v on 84J wire comming from GDR"))
(store-expert-rule '(testpoint "OLR test")
        '(dimension voltage)
        '(preconditions "check for 37V at MCJ1-T")
        '(cost 00.5000000000))
(store-expert-rule '(testpoint "ER test")
        '(dimension voltage)
        '(preconditions "check for 37V at MCJ1-G")
        '(cost 00.5000000000))
(store-expert-rule '(testpoint "PR_1 test")
        '(dimension voltage)
        '(preconditions "check for 37V at MCJ1-R ")
        '(cost 00.5000000000))
(store-expert-rule '(testpoint "BOLR test")
        '(dimension "logic code")
        '(preconditions "Look at 20h.  3E = Good")
        '(comment "logic code")
        '(cost 00.5000000000)
```

```
          '(outcome (name "20h=36")
                (causes (bad 'BOLR_84M 00.2761698900)
                     (bad 'PR1_84L 00.2761698900)
                     (bad 'ER_84L 00.2761698900)))
          '(outcome (name "20h=34")
                (causes (bad 'OLR_84J 00.3433331200)
                     (bad 'GDR_84J 00.3433331200)))
          '(outcome (name "20h something else")))
(store-expert-rule '(testpoint "PB_1 test")
          '(dimension voltage)
          '(preconditions "Check for 37V at MCJ1-V."))
(store-expert-rule '(testpoint "PBC_1 test")
          '(dimension voltage)
          '(preconditions "Check for 37V at MCJ1-Y."))
(store-expert-rule '(testpoint "CD test")
          '(dimension voltage)
          '(preconditions "Check for 37V at MITB1-3."))
(store-expert-rule '(testpoint "PR1 Feedback Test")
          '(dimension voltage)
          '(preconditions "Check for 37v at MVJ1-w (or MCTB7-8)"))
(store-expert-rule '(testpoint "20h")
          '(dimension "logic code")
          '(preconditions "Look at 20h.  3E = Good")
          '(cost 02.0000000000)
          '(outcome (name "20h = 34")
                (causes (bad 'OLR_84J 00.5000000000)
                     (bad 'GDR_84J 00.5000000000)))
          '(outcome (name "20h = 36")
                (causes (bad 'BOLR_84M 00.4000000000)
                     (bad 'PR1_84L 00.3000000000)
                     (bad 'ER_84L 00.3000000000)))
          '(outcome (name "20h = 32")
                (causes (bad '"ER Relay" 00.0000000000)
                     (bad '"KAEMR 3H-3F Contacts" 00.0000000000)
                     (bad '"ER FB Contacts" 00.0000000000)
                     (bad '"LS Box Voltage Divider" 00.0000000000)
                     (bad '"800A_fuse" 00.0000000000)
                     (bad '"MC box" 00.0000000000)
                     (bad '"shoes fuse" 00.0000000000)
                     (bad '"shoes left-side" 00.0000000000)
                     (bad '"shoes right-side" 00.0000000000)
                     (bad '"Traction motors" 00.0000000000)
                     (bad '"SC box" 00.0000000000)
                     (bad '"cables and connectors" 00.0000000000)
                     (bad '"LS coil and Feedback" 00.0000000000)
                     (bad '"Cap Discharge Switch" 00.0000000000)
                     (bad 'PBC_84N 00.0000000000)
                     (bad 'PB_84N 00.0000000000)
                     (bad 'BOLR_84M 00.0000000000)
                     (bad 'PR1_84L 00.0000000000)
                     (bad 'ER_84L 00.0000000000)
                     (bad 'OLR_84J 00.0000000000)
                     (bad 'GDR_84J 00.0000000000)
                     (bad '"friction brakes" 00.0000000000)
                     (bad '"Temp Sensors" 00.0000000000)
                     (bad '"PR1 Feedback" 00.0001708299)
```

```
            (bad 'FMV 00.0973154199)
            (bad 'RMV 00.0973154199)
            (bad '"Reverser Aux Contacts" 00.0975060400)
            (bad 'PR1 00.6695301499)))
'(outcome (name "20h = 32 in one direction only")
        (causes (bad '"LS coil and Feedback" 00.0000000000)
            (bad '"Cap Discharge Switch" 00.0000000000)
            (bad 'PBC_84N 00.0000000000)
            (bad 'PB_84N 00.0000000000)
            (bad 'BOLR_84M 00.0000000000)
            (bad 'PR1_84L 00.0000000000)
            (bad 'ER_84L 00.0000000000)
            (bad 'OLR_84J 00.0000000000)
            (bad 'GDR_84J 00.0000000000)
            (bad '"LS Box Voltage Divider" 00.0000000000)
            (bad '"800A_fuse" 00.0000000000)
            (bad '"cables and connectors" 00.0000000000)
            (bad '"shoes fuse" 00.0000000000)
            (bad '"shoes right-side" 00.0000000000)
            (bad '"shoes left-side" 00.0000000000)
            (bad '"SC box" 00.0000000000)
            (bad '"Traction motors" 00.0000000000)
            (bad '"Temp Sensors" 00.0000000000)
            (bad '"friction brakes" 00.0000000000)
            (bad '"ER Relay" 00.0000000000)
            (bad '"KAEMR 3H-3F Contacts" 00.0000000000)
            (bad '"ER FB Contacts" 00.0000000000)
            (bad '"Reverser Aux Contacts" 00.4474483200)
            (bad 'RMV 00.2485824100)
            (bad 'FMV 00.2485824100)))
'(outcome (name "20h = 3F")
        (causes (bad '"ER Relay" 00.0000000000)
            (bad '"KAEMR 3H-3F Contacts" 00.0000000000)
            (bad '"ER FB Contacts" 00.0000000000)
            (bad '"LS Box Voltage Divider" 00.0000000000)
            (bad '"800A_fuse" 00.0000000000)
            (bad '"MC box" 00.0000000000)
            (bad '"shoes fuse" 00.0000000000)
            (bad '"shoes left-side" 00.0000000000)
            (bad '"shoes right-side" 00.0000000000)
            (bad '"Traction motors" 00.0000000000)
            (bad '"SC box" 00.0000000000)
            (bad '"cables and connectors" 00.0000000000)
            (bad '"LS coil and Feedback" 00.0000000000)
            (bad '"Cap Discharge Switch" 00.0000000000)
            (bad 'PBC_84N 00.0000000000)
            (bad 'PB_84N 00.0000000000)
            (bad 'BOLR_84M 00.0000000000)
            (bad 'PR1_84L 00.0000000000)
            (bad 'ER_84L 00.0000000000)
            (bad 'OLR_84J 00.0000000000)
            (bad 'GDR_84J 00.0000000000)
            (bad 'PR1 00.0000000000)
            (bad 'FMV 00.0000000000)
            (bad 'RMV 00.0000000000)
            (bad '"Reverser Aux Contacts" 00.0000000000)
```

```
            (bad '"Temp Sensors" 00.0000000000)
            (bad '"PR1 Feedback" 00.0000000000)
            (bad '"friction brakes" 00.9693251555)))
'(outcome (name "20h = 26")
      (causes (bad '"PR1 Feedback" 00.0000000000)
            (bad '"Temp Sensors" 00.0000000000)
            (bad 'PR1 00.0000000000)
            (bad 'PR1_84L 00.0000000000)
            (bad 'GDR_84J 00.0000000000)
            (bad 'OLR_84J 00.0000000000)
            (bad '"Logic (20h)" 00.0000000000)
            (bad 'FMV 00.0000000000)
            (bad '"LS Box Voltage Divider" 00.0000000000)
            (bad '"800A_fuse" 00.0000000000)
            (bad '"MC box" 00.0000000000)
            (bad '"shoes fuse" 00.0000000000)
            (bad '"shoes left-side" 00.0000000000)
            (bad '"UUT:input" 00.0000000000)
            (bad '"shoes right-side" 00.0000000000)
            (bad '"Traction motors" 00.0000000000)
            (bad '"SC box" 00.0000000000)
            (bad '"cables and connectors" 00.0000000000)
            (bad '"LS coil and Feedback" 00.0000000000)
            (bad '"Cap Discharge Switch" 00.0000000000)
            (bad 'PBC_84N 00.0000000000)
            (bad 'PB_84N 00.0000000000)
            (bad 'BOLR_84M 00.0000000000)
            (bad 'RMV 00.0000000000)
            (bad '"Reverser Aux Contacts" 00.0000000000)
            (bad '"friction brakes" 00.0000000000)))
'(outcome (name "20h = 1E")
      (causes (bad '"ER Relay" 00.0000000000)
            (bad '"KAEMR 3H-3F Contacts" 00.0000000000)
            (bad '"ER FB Contacts" 00.0000000000)
            (bad '"PR1 Feedback" 00.0000000000)
            (bad '"LS Box Voltage Divider" 00.0000000000)
            (bad '"800A_fuse" 00.0000000000)
            (bad '"MC box" 00.0000000000)
            (bad '"shoes fuse" 00.0000000000)
            (bad '"shoes left-side" 00.0000000000)
            (bad '"shoes right-side" 00.0000000000)
            (bad '"Traction motors" 00.0000000000)
            (bad '"SC box" 00.0000000000)
            (bad '"cables and connectors" 00.0000000000)
            (bad '"LS coil and Feedback" 00.0000000000)
            (bad '"Cap Discharge Switch" 00.0000000000)
            (bad 'PBC_84N 00.0000000000)
            (bad 'PB_84N 00.0000000000)
            (bad 'BOLR_84M 00.0000000000)
            (bad 'PR1_84L 00.0000000000)
            (bad 'ER_84L 00.0000000000)
            (bad 'OLR_84J 00.0000000000)
            (bad 'GDR_84J 00.0000000000)
            (bad 'PR1 00.0000000000)
            (bad 'FMV 00.0000000000)
            (bad 'RMV 00.0000000000)
```

```
                    (bad '"Reverser Aux Contacts" 00.0000000000)
                    (bad '"friction brakes" 00.0000000000)
                    (bad '"Temp Sensors" 00.8930855900))))
(store-expert-rule '(testpoint "LS2 test 2")
          '(preconditions "Test LS 2 Mag valve and Feedback contacts."))
(store-expert-rule '(testpoint "R7 test")
          '(dimension visual)
          '(preconditions
           "Perform visual and ohm test of R7 1 ohm resistor."))
(store-expert-rule '(testpoint "R7 Resistor Test (90amp)")
          '(dimension ohm)
          '(preconditions "Perform megger test of R7 to ground."))
(store-expert-rule '(testpoint "Filter Cap Test (90amp)")
          '(dimension visual)
          '(preconditions
           "Visually inspect Filter Cap banks and ohm test fuses."))
(store-expert-rule '(testpoint "Semi-Conductor Box Tester (PTU) (90amp)")
          '(dimension Operational)
          '(preconditions
           "Perform Semi-conductor box tester procedure."))
(store-expert-rule '(testpoint "Line Reactor Test (90amp)")
          '(dimension ohm)
          '(preconditions
           "Perform megger test of the Line reactor to ground."))
(store-expert-rule '(testpoint "90A fuse test 2")
          '(dimension ohm)
          '(preconditions
           "Remove LS Box cover and perform ohm check of 90A fuse."))
(store-expert-rule '(testpoint "line reactor test")
          '(dimension visual)
          '(preconditions
           "Perform ohm and visual check of Line Reactor."))
(store-expert-rule '(testpoint "voltage divider test")
          '(dimension visual)
          '(preconditions
           "Inspect Semi-C Box Voltage Divider and circuitry "))
(store-expert-rule '(testpoint "Cap voltage test at 03h")
          '(dimension "logic code")
          '(preconditions "look at 03h, Good if between 94h and C0h")
          '(cost 02.1000000000)
          '(outcome
           (causes (bad '"R7 (1 ohm)" 00.2239999900)
                (bad '"Line react" 00.1200000000)
                (bad '"Semi-C Box Vol div" 00.1000000000)
                (bad '"UUT:input" 00.0010000000)
                (bad '"90 amp Fuse (90amp)" 00.5500000100)
                (bad '"Logic 03h" 00.0010000000)
                (bad '"shoes left-side" 00.0000000000)
                (bad '"SC box" 00.0000000000)
                (bad '"LS2 Coil and Feedback" 00.0000000000)
                (bad '"MC box" 00.0000000000)
                (bad '"Traction motors" 00.0000000000)
                (bad '"shoes right-side" 00.0000000000)
                (bad '"shoes fuse" 00.0000000000)
                (bad '"cables and connectors" 00.0000000000)
                (bad '"800A_fuse" 00.0000000000)
```

```
              (bad '"LS Box Voltage Divider" 00.0000000000)
              (bad '"R7 Resistor (90amp)" 00.0010000000)
              (bad '"Filter Caps (90amp)" 00.0010000000)
              (bad '"Semi-Conductor Box (90amp)" 00.0010000000)
              (bad '"Line Reactor (90amp)" 00.0010000000))))
(store-expert-rule '(testpoint "20h if 21h good")
         '(dimension "logic code")
         '(preconditions "Look at 20h, should be 3E")
         '(outcome (name "20h = 1E")
              (causes (bad '"Temp Logic" 00.2000000000)
                   (bad '"Temp Sensors" 00.8000000000)))
         '(outcome (name "20h = 3F")
              (causes (bad '"Slip/Slid Logic Problem" 00.2000000000)
                   (bad '"friction brakes" 00.8000000000))))
(store-expert-rule '(testpoint L18) '(dimension visual))
(store-expert-rule '(testpoint mc)
         '(dimension visual)
         '(preconditions
          "Inspect MC Box for flashing or loose connections."))
(store-expert-rule '(testpoint trac_mot)
         '(dimension visual)
         '(preconditions "Inspect TM's for flashing"))
(store-expert-rule '(testpoint sc_box)
         '(dimension visual)
         '(preconditions
          "Inspect Semi-C Box for flashing or loose connections."))
(store-expert-rule '(testpoint left_shoe)
         '(dimension visual)
         '(preconditions
          "Inspect Left Collector Shoes for good connection."))
(store-expert-rule '(testpoint right_shoe)
         '(dimension visual)
         '(preconditions
          "Inspect Right Collector Shoes for good connection."))
(store-expert-rule '(testpoint "Shoe fuse test")
         '(dimension Operational)
         '(preconditions
          "Key-up train and listen for HVAC operation."))
(store-expert-rule '(testpoint cables)
         '(dimension visual)
         '(preconditions
          "Inspect cables for flashing or loose connections."))
(store-expert-rule '(testpoint "800A Fuse Test")
         '(dimension ohm)
         '(preconditions "Perform ohm test of 800A main fuse."))
(store-expert-rule '(testpoint " Line voltage test")
         '(dimension visual)
         '(preconditions
          "Look at 0Eh, should read between A6 and C0."))
(store-expert-rule '(testpoint "Logic Swap test")
         '(dimension Operational)
         '(preconditions
          "Swap Logic with other car and run new track test."))
(store-expert-rule '(testpoint Symptom) '(dimension visual))
(store-expert-rule '(testpoint Symptom) '(dimension visual))
(store-expert-rule '(testpoint Symptom) '(dimension visual))
```

FRICTION AND DYNAMICS

```
(store-dimensions '("Logic Address" Visual Operational))
(store-preconditions
 '("Look at 49h." "Look at Logic 24h."
        "Inspect METB8 (6 and 7) for good connection."
        "Inspect METB8 (3 and 4) for good connection."
        "Inspect FBTB5 (11 and 12) for good connection."
        "Inspect FBTB3 (4 and 5) for good connection."
        "Perform DBF signal simulation Test."))
(store-cost '"Look at 49h." 00.5000000000)
(store-expert-rule '(testpoint "METB8 (3 - 4) Test")
        '(dimension Visual)
        '(preconditions
         "Inspect METB8 (3 and 4) for good connection."))
(store-expert-rule '(testpoint "FBTB3 Test")
        '(dimension Visual)
        '(preconditions
         "Inspect FBTB3 (4 and 5) for good connection."))
(store-expert-rule '(testpoint "Logic 49h Test")
        '(dimension "Logic Address")
        '(preconditions "Look at 49h."))
(store-expert-rule '(testpoint "Logic 24h Test")
        '(dimension "Logic Address")
        '(preconditions "Look at Logic 24h."))
(store-expert-rule '(testpoint "METB8 (6 - 7) Test")
        '(dimension Visual)
        '(preconditions
         "Inspect METB8 (6 and 7) for good connection."))
(store-expert-rule '(testpoint "FBTB5 Test")
        '(dimension Visual)
        '(preconditions
         "Inspect FBTB5 (11 and 12) for good connection."))
(store-expert-rule '(testpoint "FB Logic Test")
        '(dimension Operational)
        '(preconditions "Perform DBF signal simulation Test.")
        '(outcome (name "FRONT truck pressure did not decrease.")
              (causes (bad '"FBTB5 (11 - 12)" 00.0000000000)
                   (bad '"METB8 (6 - 7)" 00.0000000000)
                   (bad '"Logic XA3 Bd." 00.0000000000)
                   (bad '"Logic 49h" 00.0000000000)
                   (bad '"FBTB3 (4 - 5)" 00.4900000000)
                   (bad '"METB8 (3 - 4)" 00.4900000000)))
        '(outcome (name "REAR truck pressure did not decrease.")
              (causes (bad '"FBTB3 (4 - 5)" 00.0000000000)
                   (bad '"METB8 (3 - 4)" 00.0000000000)
                   (bad '"FBTB5 (11 - 12)" 00.4900000000)
                   (bad '"METB8 (6 - 7)" 00.4900000000)
                   (bad '"Logic XA3 Bd." 00.0000000000)
                   (bad '"Logic 49h" 00.0000000000))))
```

MOL

```
(store-dimensions
 '("Visual Inspection" resistance
                   current
                   voltage
                   "GDR latched"
                   "OLR latched"
                   "BOLR latched"))
(store-preconditions
 '("check if relays  BOLR, OLR and GDR are latch"
   "use \"Meger\" to check if motor resistance is <10 Mohm"
   "Run TT monitoring Logic locations 00h, 01h, 02h, 0Fh."
   "check all transducers' output with voltmeter, should be <50mA"
   "Visually inspect complete Propulsion package"
   "if any of them is, click on \"bad\""
   "visually inspect motors"
   "Thoroughly inspect and meger Front truck motors."
   "Thoroughly inspect and meger Rear truck motors."))
(store-cost '"use \"Meger\" to check if motor resistance is <10 Mohm" 02.5000000000)
(store-cost '"Run TT monitoring Logic locations 00h, 01h, 02h, 0Fh." 03.0000000000)
(store-cost '"check all transducers' output with voltmeter, should be <50mA"
         02.0000000000)
(store-cost '"Visually inspect complete Propulsion package" 02.0000000000)
(store-expert-rule '(testpoint "TDRs Test")
               '(dimension voltage)
               '(preconditions
                 "check all transducers' output with voltmeter, should be <50mA")
               '(comment "voltage at transducer"))
(store-expert-rule '(testpoint "Visual Test")
               '(dimension "Visual Inspection")
               '(preconditions "visually inspect motors")
               '(comment "Visual Inspection"))
(store-expert-rule '(testpoint "TM Meger Test")
               '(dimension resistance)
               '(preconditions
                 "use \"Meger\" to check if motor resistance is <10 Mohm")
               '(comment "resistance of motors")
               '(outcome (name "resistance is between 1 Mohm and 10 Mohm")
                      (causes (bad '"Meger Motors " 00.0189000000)))
               '(outcome (name "resistance less then 100 Kohm")
                      (causes (bad '"Meger Motors " 00.8839000000)))
               '(outcome (name "resistance between 100 Kohm and 1Mohm")
                      (causes (bad '"Meger Motors " 00.1034000000))))
(store-expert-rule '(testpoint "Visual Inspection")
               '(dimension "Visual Inspection")
               '(preconditions
                 "Visually inspect complete Propulsion package"))
(store-expert-rule '(testpoint "Front Truck Insp.")
               '(dimension "Visual Inspection")
               '(preconditions
                 "Thoroughly inspect and meger Front truck motors."))
(store-expert-rule '(testpoint "Rear Truck Insp.")
               '(dimension "Visual Inspection")
               '(preconditions
                 "Thoroughly inspect and meger Rear truck motors."))
```

```
(store-expert-rule '(testpoint "Truck Test 1")
        '(dimension "Visual Inspection")
        '(preconditions
         "Run TT monitoring Logic locations 00h, 01h, 02h, 0Fh.")
        '(outcome
         (name "Front current (00h) much greater than Rear (01h).")
         (causes (bad '"Front Truck" 01.0000000000)))
        '(outcome
         (name "Rear Current (01h) much greater than Front (00h).")
         (causes (bad '"Rear Truck" 01.0000000000))))
(store-expert-rule '(testpoint Symptom)
        '(dimension "BOLR latched")
        '(outcome
         (causes (bad '"Meger Motors " 00.0486741100)
              (bad '"Visual Inspection Complete Package" 00.0954436400)
              (bad 'Transducers 00.0945812100)
              (bad '"Visual Motors" 00.6684889700))))
(store-expert-rule '(testpoint Symptom)
        '(dimension "OLR latched")
        '(outcome
         (causes (bad 'Transducers 00.1088331300)
              (bad '"Visual Inspection Complete Package" 00.1090516700)
              (bad '"Visual Motors" 00.7630338900))))
(store-expert-rule '(testpoint Symptom)
        '(dimension "GDR latched")
        '(outcome
         (causes (bad 'Transducers 00.0960396600)
              (bad '"Visual Inspection Complete Package" 00.1439614800)
              (bad '"Visual Motors" 00.6719836300))))
(store-expert-rule '(testpoint Symptom)
        '(dimension "BOLR latched")
        '(outcome
         (causes (bad '"Meger Motors " 00.0486741100)
              (bad '"Visual Inspection Complete Package" 00.0954436400)
              (bad 'Transducers 00.0945812100)
              (bad '"Visual Motors" 00.6684889700))))
(store-expert-rule '(testpoint Symptom)
        '(dimension "OLR latched")
        '(outcome
         (causes (bad 'Transducers 00.1088331300)
              (bad '"Visual Inspection Complete Package" 00.1090516700)
              (bad '"Visual Motors" 00.7630338900))))
(store-expert-rule '(testpoint Symptom)
        '(dimension "GDR latched")
        '(outcome
         (causes (bad 'Transducers 00.0960396600)
              (bad '"Visual Inspection Complete Package" 00.1439614800)
              (bad '"Visual Motors" 00.6719836300))))
```

FLASHING MOL

```
(store-dimensions
 '("Visual Inspection" resistance
          current
          voltage
```

```
                    "GDR latched"
                    "OLR latched"
                    "BOLR latched"))
(store-preconditions
 '("check if relays  BOLR, OLR and GDR are latch"
   "use \"Meger\" to check if motor resistance is <10 Mohm"
   "Run TT monitoring Logic locations 00h, 01h, 02h, 0Fh."
   "check all transducers' output with voltmeter, should be <50mA"
   "Visually inspect complete Propulsion package"
   "if any of them is, click on \"bad\""
   "visually inspect motors"
   "Thoroughly inspect and meger Front truck motors."
   "Thoroughly inspect and meger Rear truck motors."))
(store-cost '"use \"Meger\" to check if motor resistance is <10 Mohm" 02.5000000000)
(store-cost '"Run TT monitoring Logic locations 00h, 01h, 02h, 0Fh." 03.0000000000)
(store-cost '"check all transducers' output with voltmeter, should be <50mA"
        02.0000000000)
(store-cost '"Visually inspect complete Propulsion package" 02.0000000000)
(store-expert-rule '(testpoint "TDRs Test")
             '(dimension voltage)
             '(preconditions
               "check all transducers' output with voltmeter, should be <50mA")
             '(comment "voltage at transducer"))
(store-expert-rule '(testpoint "Visual Test")
             '(dimension "Visual Inspection")
             '(preconditions "visually inspect motors")
             '(comment "Visual Inspection"))
(store-expert-rule '(testpoint "TM Meger Test")
             '(dimension resistance)
             '(preconditions
               "use \"Meger\" to check if motor resistance is <10 Mohm")
             '(comment "resistance of motors")
             '(outcome (name "resistance is between 1 Mohm and 10 Mohm")
                    (causes (bad '"Meger Motors " 00.0189000000)))
             '(outcome (name "resistance less then 100 Kohm")
                    (causes (bad '"Meger Motors " 00.8839000000)))
             '(outcome (name "resistance between 100 Kohm and 1Mohm")
                    (causes (bad '"Meger Motors " 00.1034000000))))
(store-expert-rule '(testpoint "Visual Inspection")
             '(dimension "Visual Inspection")
             '(preconditions
               "Visually inspect complete Propulsion package"))
(store-expert-rule '(testpoint "Front Truck Insp.")
             '(dimension "Visual Inspection")
             '(preconditions
               "Thoroughly inspect and meger Front truck motors."))
(store-expert-rule '(testpoint "Rear Truck Insp.")
             '(dimension "Visual Inspection")
             '(preconditions
               "Thoroughly inspect and meger Rear truck motors."))
(store-expert-rule '(testpoint "Truck Test 1")
             '(dimension "Visual Inspection")
             '(preconditions
               "Run TT monitoring Logic locations 00h, 01h, 02h, 0Fh.")
             '(outcome
               (name "Front current (00h) much greater than Rear (01h).")
```

```
        (causes (bad '"Front Truck" 01.0000000000)))
       '(outcome
        (name "Rear Current (01h) much greater than Front (00h).")
        (causes (bad '"Rear Truck" 01.0000000000))))
(store-expert-rule '(testpoint Symptom)
       '(dimension "BOLR latched")
       '(outcome
        (causes (bad '"Meger Motors " 00.0486741100)
             (bad '"Visual Inspection Complete Package" 00.0954436400)
             (bad 'Transducers 00.0945812100)
             (bad '"Visual Motors" 00.6684889700))))
(store-expert-rule '(testpoint Symptom)
       '(dimension "OLR latched")
       '(outcome
        (causes (bad 'Transducers 00.1088331300)
             (bad '"Visual Inspection Complete Package" 00.1090516700)
             (bad '"Visual Motors" 00.7630338900))))
(store-expert-rule '(testpoint Symptom)
       '(dimension "GDR latched")
       '(outcome
        (causes (bad 'Transducers 00.0960396600)
             (bad '"Visual Inspection Complete Package" 00.1439614800)
             (bad '"Visual Motors" 00.6719836300))))
(store-expert-rule '(testpoint Symptom)
       '(dimension "BOLR latched")
       '(outcome
        (causes (bad '"Meger Motors " 00.0486741100)
             (bad '"Visual Inspection Complete Package" 00.0954436400)
             (bad 'Transducers 00.0945812100)
             (bad '"Visual Motors" 00.6684889700))))
(store-expert-rule '(testpoint Symptom)
       '(dimension "OLR latched")
       '(outcome
        (causes (bad 'Transducers 00.1088331300)
             (bad '"Visual Inspection Complete Package" 00.1090516700)
             (bad '"Visual Motors" 00.7630338900))))
(store-expert-rule '(testpoint Symptom)
       '(dimension "GDR latched")
       '(outcome
        (causes (bad 'Transducers 00.0960396600)
             (bad '"Visual Inspection Complete Package" 00.1439614800)
             (bad '"Visual Motors" 00.6719836300))))
```

JERKING IN BRAKING

```
(store-dimensions
 '("Jerks at 35 mph" "Jerks at 45 mph"
        "Jerks at any speed"
        "logic code"
        visual
        Operational))
(store-preconditions
 '("check if contactors pick up and drop out."
  "look at control box and semiconduct box."
  "test or swap logic box."
```

```
  "look at memory location 67h, should be 00h"
  "look at memory location AEh, should be 00"
  "look at memory location 20h, should be 3E "
  "look at memory location 21h"
  "look at memory location 9Dh, should be 00"
  "look at memory location D1, must be stable"
  "should be 87 in power, 08 in braking, 0B in regen. braking"
  "measure air flow from blower motor"
  "Perform test of Temp Sensor Loop continuity."
  "If value is anything else, Run \"No Current\" Model"
  "Check Friction Brake Tach sensors and rings"
  "Inspect PBC HV contacts"
  "Check Load Weigh Transducer output."
  "Check for static output of Transducers, should be < 50mA."
  "Check Prop tach sensors and rings"
  "Inspect LS Box Voltage Divider for loose connections."
  "Inspect Collector Shoes for proper connection."
  "Perform F3/F4 Timing Test at METB during MLTT."
  "Perform F3/F4 Timing Test at METB."
  "Perform F3/F4 manual ops and visual test."
  "Perform F5/F6 Timing Test at METB."
  "Perform F5/F6 Timing Test at METB during MLTT."
  "Perform F5/F6 manual ops and visual test."
  "Visually inspect GPA LEDs and connectors."
  "Vibration test LS1 while it is actuated."
  "Swap Logic with other car and re-run track test."
  "Visually inspect Semi-C Box for proper connections."
  "Perform Semi-C Box Tester Procedure."
  "Visually inspect motor reactor."
  "Visually inspect propulsion package"
  "Vibration Test Temp. Sensors"))
(store-cost '"look at memory location 67h, should be 00h" 00.2000000000)
(store-cost '"look at memory location AEh, should be 00" 00.2000000000)
(store-cost '"look at memory location 20h, should be 3E " 00.1200000000)
(store-cost '"look at memory location 21h" 00.1000000000)
(store-cost '"look at memory location 9Dh, should be 00" 00.2000000000)
(store-cost '"look at memory location D1, must be stable" 00.2000000000)
(store-cost '"should be 87 in power, 08 in braking, 0B in regen. braking"
        00.1000000000)
(store-cost '"measure air flow from blower motor" 03.0000000000)
(store-cost '"Perform test of Temp Sensor Loop continuity." 10.0000000000)
(store-cost '"If value is anything else, Run \"No Current\" Model" 00.1000000000)
(store-cost '"Perform F3/F4 Timing Test at METB during MLTT." 80.0000000000)
(store-cost '"Perform F3/F4 Timing Test at METB." 02.0000000000)
(store-cost '"Perform F3/F4 manual ops and visual test." 03.0000000000)
(store-cost '"Perform F5/F6 Timing Test at METB." 02.0000000000)
(store-cost '"Perform F5/F6 Timing Test at METB during MLTT." 80.0000000000)
(store-cost '"Perform F5/F6 manual ops and visual test." 03.0000000000)
(store-cost '"Vibration test LS1 while it is actuated." 01.1000000000)
(store-cost '"Swap Logic with other car and re-run track test." 10.0000000000)
(store-cost '"Perform Semi-C Box Tester Procedure." 30.0000000000)
(store-cost '"Visually inspect motor reactor." 100.0000000000)
(store-cost '"Visually inspect propulsion package" 00.7500000000)
(store-cost '"Vibration Test Temp. Sensors" 01.2000000000)
(store-expert-rule '(testpoint "Semi C Box Visual Test")
            '(dimension visual)
```

```
            '(preconditions
             "Visually inspect Semi-C Box for proper connections."))
(store-expert-rule '(testpoint " 20h")
            '(dimension "logic code")
            '(preconditions "look at memory location 20h, should be 3E ")
            '(outcome (name "20h = 3F")
                  (causes (bad '"Friction brakes" 00.9068011288)))
            '(outcome (name "20h = 1E")
                  (causes (bad '"Temp Sensor Logic" 00.2000000000)
                        (bad '"Temp Sensor" 00.8000000000))))
(store-expert-rule '(testpoint " D1h")
            '(dimension "logic code")
            '(preconditions "look at memory location D1, must be stable")
            '(cost 01.5000000000)
            '(outcome (causes (bad '"Load Weigh Transducer" 00.9592499259))))
(store-expert-rule '(testpoint " AEh")
            '(dimension "logic code")
            '(preconditions "look at memory location AEh, should be 00")
            '(cost 01.4000000000)
            '(outcome (name "AEh = FFh") (causes (bad '"TDR's" 00.8250000019)))
            '(outcome (name "something else")
                  (causes (bad '"logic box" 01.0000000000))))
(store-expert-rule '(testpoint "F3/F4 MLTT")
            '(dimension Operational)
            '(preconditions
             "Perform F3/F4 Timing Test at METB during MLTT."))
(store-expert-rule '(testpoint "Voltage Divider Test")
            '(dimension visual)
            '(preconditions
             "Inspect LS Box Voltage Divider for loose connections."))
(store-expert-rule '(testpoint "Prop Tach/Tach Ring Test")
            '(preconditions "Check Prop tach sensors and rings"))
(store-expert-rule '(testpoint "Visual propulsion ")
            '(dimension visual)
            '(preconditions "Visually inspect propulsion package"))
(store-expert-rule '(testpoint "FB Test")
            '(dimension visual)
            '(preconditions
             "Check Friction Brake Tach sensors and rings"))
(store-expert-rule '(testpoint "GPA Test")
            '(dimension visual)
            '(preconditions "Visually inspect GPA LEDs and connectors."))
(store-expert-rule '(testpoint "LW Transducer Test")
            '(preconditions "Check Load Weigh Transducer output."))
(store-expert-rule '(testpoint "TDR Test")
            '(preconditions
             "Check for static output of Transducers, should be < 50mA."))
(store-expert-rule '(testpoint "F3/F4 Test")
            '(dimension Operational)
            '(preconditions "Perform F3/F4 Timing Test at METB."))
(store-expert-rule '(testpoint "Line Sw Test")
            '(dimension Operational)
            '(preconditions "Vibration test LS1 while it is actuated."))
(store-expert-rule '(testpoint "Shoe Test")
            '(dimension visual)
            '(preconditions
```

```
                "Inspect Collector Shoes for proper connection."))
(store-expert-rule '(testpoint "Semi C Box Tester Test")
             '(dimension Operational)
             '(preconditions "Perform Semi-C Box Tester Procedure."))
```

JERKING IN PROPULSION

```
(store-dimensions
 '("Jerks at 35 mph" "Jerks at 45 mph"
                "Jerks at any speed"
                "logic code"
                visual
                Operational))
(store-preconditions
 '("check if contactors pick up and drop out."
   "look at control box and semiconduct box."
   "test or swap logic box."
   "look at memory location 67h, should be 00h"
   "look at memory location AEh, should be 00"
   "look at memory location 20h, should be 3E "
   "look at memory location 21h"
   "look at memory location 9Dh, should be 00"
   "look at memory location D1, must be stable"
   "should be 87 in power, 08 in braking, 0B in regen. braking"
   "measure air flow from blower motor"
   "Perform test of Temp Sensor Loop continuity."
   "If value is anything else, Run \"No Current\" Model"
   "Check Friction Brake Tach sensors and rings"
   "Inspect PBC HV contacts"
   "Check Load Weigh Transducer output."
   "Check for static output of Transducers, should be < 50mA."
   "Check Prop tach sensors and rings"
   "Inspect LS Box Voltage Divider for loose connections."
   "Inspect Collector Shoes for proper connection."
   "Perform F3/F4 Timing Test at METB during MLTT."
   "Perform F3/F4 Timing Test at METB."
   "Perform F3/F4 manual ops and visual test."
   "Perform F5/F6 Timing Test at METB."
   "Perform F5/F6 Timing Test at METB during MLTT."
   "Perform F5/F6 manual ops and visual test."
   "Visually inspect GPA LEDs and connectors."
   "Vibration test LS1 while it is actuated."
   "Swap Logic with other car and re-run track test."
   "Visually inspect Semi-C Box for proper connections."
   "Perform Semi-C Box Tester Procedure."
   "Visually inspect motor reactor."
   "Visually inspect propulsion package"
   "Vibration Test Temp. Sensors"))
(store-cost '"look at memory location 67h, should be 00h" 00.2000000000)
(store-cost '"look at memory location AEh, should be 00" 00.2000000000)
(store-cost '"look at memory location 20h, should be 3E " 00.1200000000)
(store-cost '"look at memory location 21h" 00.1000000000)
(store-cost '"look at memory location 9Dh, should be 00" 00.2000000000)
(store-cost '"look at memory location D1, must be stable" 00.2000000000)
(store-cost '"should be 87 in power, 08 in braking, 0B in regen. braking"
```

```
        00.1000000000)
(store-cost '"measure air flow from blower motor" 03.0000000000)
(store-cost '"Perform test of Temp Sensor Loop continuity." 10.0000000000)
(store-cost '"If value is anything else, Run \"No Current\" Model" 00.1000000000)
(store-cost '"Perform F3/F4 Timing Test at METB during MLTT." 80.0000000000)
(store-cost '"Perform F3/F4 Timing Test at METB." 02.0000000000)
(store-cost '"Perform F3/F4 manual ops and visual test." 03.0000000000)
(store-cost '"Perform F5/F6 Timing Test at METB." 02.0000000000)
(store-cost '"Perform F5/F6 Timing Test at METB during MLTT." 80.0000000000)
(store-cost '"Perform F5/F6 manual ops and visual test." 03.0000000000)
(store-cost '"Vibration test LS1 while it is actuated." 01.1000000000)
(store-cost '"Swap Logic with other car and re-run track test." 10.0000000000)
(store-cost '"Perform Semi-C Box Tester Procedure." 30.0000000000)
(store-cost '"Visually inspect motor reactor." 100.0000000000)
(store-cost '"Visually inspect propulsion package" 00.7500000000)
(store-cost '"Vibration Test Temp. Sensors" 01.2000000000)
(store-expert-rule '(testpoint "Semi C Box Visual Test")
        '(dimension visual)
        '(preconditions
         "Visually inspect Semi-C Box for proper connections."))
(store-expert-rule '(testpoint " 20h")
        '(dimension "logic code")
        '(preconditions "look at memory location 20h, should be 3E ")
        '(outcome (name "20h = 3F")
              (causes (bad '"Friction brakes" 00.9068011288)))
        '(outcome (name "20h = 1E")
              (causes (bad '"Temp Sensor Logic" 00.2000000000)
                   (bad '"Temp Sensor" 00.8000000000))))
(store-expert-rule '(testpoint " D1h")
        '(dimension "logic code")
        '(preconditions "look at memory location D1, must be stable")
        '(cost 01.5000000000)
        '(outcome (causes (bad '"Load Weigh Transducer" 00.9592499259))))
(store-expert-rule '(testpoint " AEh")
        '(dimension "logic code")
        '(preconditions "look at memory location AEh, should be 00")
        '(cost 01.4000000000)
        '(outcome (name "AEh = FFh") (causes (bad '"TDR's" 00.8250000019)))
        '(outcome (name "something else")
              (causes (bad '"logic box" 01.0000000000))))
(store-expert-rule '(testpoint "F3/F4 MLTT")
        '(dimension Operational)
        '(preconditions
         "Perform F3/F4 Timing Test at METB during MLTT."))
(store-expert-rule '(testpoint "Voltage Divider Test")
        '(dimension visual)
        '(preconditions
         "Inspect LS Box Voltage Divider for loose connections."))
(store-expert-rule '(testpoint "Prop Tach/Tach Ring Test")
        '(preconditions "Check Prop tach sensors and rings"))
(store-expert-rule '(testpoint "Visual propulsion ")
        '(dimension visual)
        '(preconditions "Visually inspect propulsion package"))
(store-expert-rule '(testpoint "FB Test")
        '(dimension visual)
        '(preconditions
```

```
               "Check Friction Brake Tach sensors and rings"))
(store-expert-rule '(testpoint "GPA Test")
             '(dimension visual)
             '(preconditions "Visually inspect GPA LEDs and connectors."))
(store-expert-rule '(testpoint "LW Transducer Test")
             '(preconditions "Check Load Weigh Transducer output."))
(store-expert-rule '(testpoint "TDR Test")
             '(preconditions
               "Check for static output of Transducers, should be < 50mA."))
(store-expert-rule '(testpoint "F3/F4 Test")
             '(dimension Operational)
             '(preconditions "Perform F3/F4 Timing Test at METB."))
(store-expert-rule '(testpoint "Line Sw Test")
             '(dimension Operational)
             '(preconditions "Vibration test LS1 while it is actuated."))
(store-expert-rule '(testpoint "Shoe Test")
             '(dimension visual)
             '(preconditions
               "Inspect Collector Shoes for proper connection."))
(store-expert-rule '(testpoint "Semi C Box Tester Test")
             '(dimension Operational)
             '(preconditions "Perform Semi-C Box Tester Procedure."))
```

NO DYNAMIC BRAKING

```
(store-dimensions
 '("erratic always" "jerking in breaking"
              Voltage
              "Logic Address"
              Operational
              Visual))
(store-preconditions
 '("Read Value of 21h in Braking. Should read 08"
   "Run TT. Train must draw good \"I\" before braking can occur."
   "Read 3Dh in Braking. Should = 1B for 2 s, then 0B"
   "Check for 37v at MCJ1-f"
   "Check for 37v at MCJ1-g"
   "In Shop - Supply Ground at METB4-13. LC should actuate"
   "Manually Actuate LC and check for 37v at METB5-15"
   "Inspect PBC HV contacts and cable connections"
   "Inspect LC HV contacts and cable connections"))
(store-cost '"Read Value of 21h in Braking. Should read 08" 00.8000000000)
(store-cost '"Run TT. Train must draw good \"I\" before braking can occur."
       00.5000000000)
(store-expert-rule '(testpoint "LC HV Circuit Test")
             '(dimension Visual)
             '(preconditions
               "Inspect LC HV contacts and cable connections"))
(store-expert-rule '(testpoint "Logic 3D Test")
             '(dimension "Logic Address")
             '(preconditions
               "Read 3Dh in Braking. Should = 1B for 2 s, then 0B")
             '(outcome (causes (bad '"Logic 3D" 01.0000000000))))
(store-expert-rule '(testpoint "DBCR Test")
             '(dimension Voltage)
```

```
            '(preconditions "Check for 37v at MCJ1-f"))
(store-expert-rule '(testpoint "PBC Aux Test")
            '(dimension Voltage)
            '(preconditions "Check for 37v at MCJ1-g"))
(store-expert-rule '(testpoint "Loop Contactor Test")
            '(dimension Operational)
            '(preconditions
             "In Shop - Supply Ground at METB4-13. LC should actuate"))
(store-expert-rule '(testpoint "Power Mode Test")
            '(dimension Operational)
            '(preconditions
             "Run TT. Train must draw good \"I\" before braking can occur.")
            '(outcome (causes (bad '"Current Draw" 01.0000000000))))
(store-expert-rule '(testpoint L11) '(dimension Operational))
(store-expert-rule '(testpoint "Loop Cont. FB Test")
            '(dimension Voltage)
            '(preconditions
             "Manually Actuate LC and check for 37v at METB5-15"))
(store-expert-rule '(testpoint "Logic 21h Test")
            '(dimension "Logic Address")
            '(preconditions
             "Read Value of 21h in Braking. Should read 08")
            '(outcome (causes (bad '"Logic 3D" 00.3437500000))))
(store-expert-rule '(testpoint "PBC HV Circuit Test")
            '(dimension Visual)
            '(preconditions
             "Inspect PBC HV contacts and cable connections"))
(store-expert-rule '(testpoint Symptom)
            '(dimension Voltage)
            '(outcome
             (causes (bad '"jerking in propulsion - mostly" 00.2820512865))))
(store-expert-rule '(testpoint Symptom)
            '(dimension "jerking in breaking")
            '(outcome
             (causes (bad '"jerking in breaking - mostly" 00.2820512865))))
(store-expert-rule '(testpoint Symptom)
            '(dimension "Logic Address")
            '(outcome
             (causes (bad '"erratic always" 00.0581395300)
                  (bad '"Logic Address" 00.2906976659))))
(store-expert-rule '(testpoint Symptom)
            '(dimension "erratic always")
            '(outcome (causes (bad '"erratic always" 00.2820512865))))
```

APPENDIX D

GLOSSARY

AI Artificial Intelligence.
Analog to digital conversion (A/D conversion) A circuit that converts analog values to digital (numeric) values.
Antiparallel Parallel connection of diode and thyristor in such a way that no current is allowed through.
BART Bay Area Rapid Transit District.
Binary A base 2 numbering system (using only the digits 0 and 1).
BOLR Brake Overload Relay.
Brush A carbon conductor that maintains an electric connection between stationary and moving parts of a motor.
Byte A string of eight bits, operate as a unit.
CD-ROM Read Only memory on a compact disk.
Contactor One or more sets of contacts that are open or closed by magnetic coil. The contactor is similar to relay but normally larger.
COTS Commercial off the shelf.
DAQ Data acquisition card.
DC chopper Type of electric motor which use thyristors for power control.
DC Direct current, current that flows in only one direction.
Digital to Analog conversion (D/A conversion) A digital value whose instantaneous magnitude is converted to its equivalent analog signal.
Diodes A two-terminal solid state semiconductor that allow current flow in only one direction.
Duty Cycle The ratio of working time to total time for a motor that operates intermittently.
EPROM Erasable programmable read-only memory. A memory that can be erased with ultraviolet light then reprogrammed with electrical signal.
FSR Failure Service Reports. Report used by WMATA maintenance staff.
Fuse A device designed as a one-time protection against overcurrent or short-circuit current.
FWD Free willing diode.
GDR Ground detect relay.
HCI Human-computer interface.
IC Integrated circuit. A solid state device that includes combinations of circuit elements (resistors, capacitors, transistors) that are fabricated on a single continuos substrate.
ICAT Intelligent Computer-Aided Troubleshooting. Software AI shell made by Titan Ltd.
If-then statement. Principle used in rule-based knowledge systems.
Kilobyte 1024 bytes.
kS/s Kilo samples per second. Sampling rate of 1000 acquired input signal points in one second.
LACMTA Los Angeles County Metropolitan Transportation Authority.
LED Light emitting diode. A two lead solid state device that produces a small amount of light when biased.
LISP Programming language, primary used in AI applications.
Logic General term for relay circuits, digital circuits, and programmable instruction to perform required decision making and computational function.
MARS Maintenance and Reliability System.
MARTA Metropolitan Atlanta Rapid Transit Authority.
MBR Model-based reasoning.
MBTA Massachusetts Bay Transportation Authority.
MDTA Metro-Dade Transit Authority.
MIS Management Information Systems.
MTA Maryland Mass Transit Administration.
NTF No Trouble Found. Code used for non-repeatable failures.

OLR Overload Relay.
OLX Overload Auxiliary Relay.
RAM Random access memory. The type of memory which allows reading and writing.
RTA Greater Cleveland Regional Transit Authority.
SEPTA Southeastern Pennsylvania Transportation Authority.
Snubber circuit Circuit used for easing the stress on thyristor.
Thyristors Solid state device used for switching large voltages and currents.
WMATA Washington Metropolitan Area Transit Authority.

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The National Academy of Sciences is a private, nonprofit, self-perpetuating society of distinguished scholars engaged in scientific and engineering research, dedicated to the furtherance of science and technology and to their use for the general welfare. Upon the authority of the charter granted to it by the Congress in 1863, the Academy has a mandate that requires it to advise the federal government on scientific and technical matters. Dr. Bruce M. Alberts is president of the National Academy of Sciences.

The National Academy of Engineering was established in 1964, under the charter of the National Academy of Sciences, as a parallel organization of outstanding engineers. It is autonomous in its administration and in the selection of its members, sharing with the National Academy of Sciences the responsibility for advising the federal government. The National Academy of Engineering also sponsors engineering programs aimed at meeting national needs, encourages education and research, and recognizes the superior achievements of engineers. Dr. William A. Wulf is president of the National Academy of Engineering.

The Institute of Medicine was established in 1970 by the National Academy of Sciences to secure the services of eminent members of appropriate professions in the examination of policy matters pertaining to the health of the public. The Institute acts under the responsibility given to the National Academy of Sciences by its congressional charter to be an adviser to the federal government and, upon its own initiative, to identify issues of medical care, research, and education. Dr. Kenneth I. Shine is president of the Institute of Medicine.

The National Research Council was organized by the National Academy of Sciences in 1916 to associate the broad community of science and technology with the Academy's purpose of furthering knowledge and advising the federal government. Functioning in accordance with general policies determined by the Academy, the Council has become the principal operating agency of both the National Academy of Sciences and the National Academy of Engineering in providing services to the government, the public, and the scientific and engineering communities. The Council is administered jointly by both the Academies and the Institute of Medicine. Dr. Bruce M. Alberts and Dr. William A. Wulf are chairman and vice chairman, respectively, of the National Research Council.

Abbreviations used without definitions in TRB publications:

AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
IEEE	Institute of Electrical and Electronics Engineers
ITE	Institute of Transportation Engineers
NCHRP	National Cooperative Highway Research Program
NCTRP	National Cooperative Transit Research and Development Program
NHTSA	National Highway Traffic Safety Administration
SAE	Society of Automotive Engineers
TCRP	Transit Cooperative Research Program
TRB	Transportation Research Board
U.S.DOT	United States Department of Transportation