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# A METHODOLOGY FOR EVALUATING THE MAINTENANCE OF HIGH SPEED PASSENGER TRAIN TRUCKS

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DECEMBER 1978

FINAL REPORT


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Prepared For

U. S. DEPARTMENT OF TRANSPORTATION
FEDERAL RAILROAD ADMINISTRATION
Office of Research and Development
Washington DC 20590

Track + Structures

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16. Abstract

This report describes the application of a methodology, the simulation cost model (SCM), to the economic aspects of maintaining high speed passenger train trucks. The methodology provides a description of truck maintenance, gives the annual costs for this maintenance, and allows sensitivity analyses and time projections to be made.

The report first reviews and classifies present and near-term trucks for consideration by the methodology. The SCM methodology is then presented and described. It is applied to two trucks -- the truck of the Metroliner (powered) and that of the Amcoaches (unpowered). These applications are used to indicate data requirements, to present the type of results obtainable from the technique, and to show how the results can be used. The relationship between the SCM and truck specifications is explored.

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## PREFACE

This work was conducted for the Federal Railroad Administration through the Transportation Systems Center (TSC) in Cambridge, Massachusetts. Mr. Kevin W. Yearwood was the TSC technical monitor. Messrs. Raymond Ehrenbeck and How M. Wong, both of TSC, also provided technical assistance for this work.

The Budd Company was subcontractor to Shaker Research Corporation and provided much of the information contained in Section 2.0. This contribution and other assistance from Budd, particularly from Mr. Stephen Shapiro, Project Engineer, to this work are acknowledged.

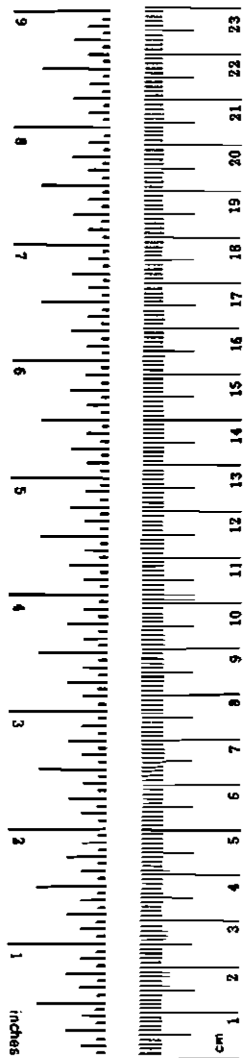
Other contributors to this work are also acknowledged. These include: for the Wilmington Delaware Metroliner Maintenance Facility — Messrs. D. L. Muyskens, Assistant General Manager, and A. Zecca, Car Shop Supervisor; for the 30th Street Philadelphia Amtrak Maintenance Facility — Messrs. R. Randall, Manager of the Maintenance Facility, J. Foss, Superintendent of Maintenance, S. Brewer, General Foreman, J. Morabito, General Foreman, and K. Cooper, General Supervisor of Management Systems; for the Canadian National Railroad — Messrs. R. W. Rust, Technical Specialist, Turbotrain Facilities, and J. N. McConnell, Mechanical Equipment Officer - M. P. Equipment Department.

# METRIC CONVERSION FACTORS

## Approximate Conversions to Metric Measures

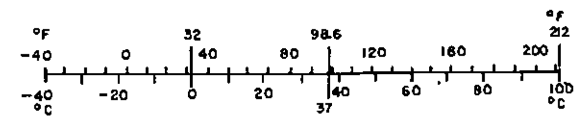
| Symbol | When You Know | Multiply by | To Find | Symbol |
|---|---|---|---|---|
| | **LENGTH** | | | |
| in | inches | *2.5 | centimeters | cm |
| ft | feet | 30 | centimeters | cm |
| yd | yards | 0.9 | meters | m |
| mi | miles | 1.6 | kilometers | km |
| | **AREA** | | | |
| $in^2$ | square inches | 6.5 | square centimeters | $cm^2$ |
| $ft^2$ | square feet | 0.09 | square meters | $m^2$ |
| $yd^2$ | square yards | 0.8 | square meters | $m^2$ |
| $mi^2$ | square miles | 2.6 | square kilometers | $km^2$ |
| | acres | 0.4 | hectares | ha |
| | **MASS (weight)** | | | |
| oz | ounces | 28 | grams | g |
| lb | pounds | 0.45 | kilograms | kg |
| | short tons (2000 lb) | 0.9 | tonnes | t |
| | **VOLUME** | | | |
| tsp | teaspoons | 5 | milliliters | ml |
| Tbsp | tablespoons | 15 | milliliters | ml |
| fl oz | fluid ounces | 30 | milliliters | ml |
| c | cups | 0.24 | liters | l |
| pt | pints | 0.47 | liters | l |
| qt | quarts | 0.95 | liters | l |
| gal | gallons | 3.8 | liters | l |
| $ft^3$ | cubic feet | 0.03 | cubic meters | $m^3$ |
| $yd^3$ | cubic yards | 0.76 | cubic meters | $m^3$ |
| | **TEMPERATURE (exact)** | | | |
| °F | Fahrenheit temperature | 5/9 (after subtracting 32) | Celsius temperature | °C |

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.




## Approximate Conversions from Metric Measures

| Symbol | When You Know | Multiply by | To Find | Symbol |
|---|---|---|---|---|
| | **LENGTH** | | | |
| mm | millimeters | 0.04 | inches | in |
| cm | centimeters | 0.4 | inches | in |
| m | meters | 3.3 | feet | ft |
| m | meters | 1.1 | yards | yd |
| km | kilometers | 0.6 | miles | mi |
| | **AREA** | | | |
| $cm^2$ | square centimeters | 0.16 | square inches | $in^2$ |
| $m^2$ | square meters | 1.2 | square yards | $yd^2$ |
| $km^2$ | square kilometers | 0.4 | square miles | $mi^2$ |
| ha | hectares (10,000 $m^2$) | 2.5 | acres | |
| | **MASS (weight)** | | | |
| g | grams | 0.035 | ounces | oz |
| kg | kilograms | 2.2 | pounds | lb |
| t | tonnes (1000 kg) | 1.1 | short tons | |
| | **VOLUME** | | | |
| ml | milliliters | 0.03 | fluid ounces | fl oz |
| l | liters | 2.1 | pints | pt |
| l | liters | 1.06 | quarts | qt |
| l | liters | 0.26 | gallons | gal |
| $m^3$ | cubic meters | 35 | cubic feet | $ft^3$ |
| $m^3$ | cubic meters | 1.3 | cubic yards | $yd^3$ |
| | **TEMPERATURE (exact)** | | | |
| °C | Celsius temperature | 9/5 (then add 32) | Fahrenheit temperature | °F |



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# LIST OF SYMBOLS

| | |
|---|---|
| A | Representative age of units in path, years |
| C | Proportion of arriving units which branches, at a branch node, to the path intended either for defective units or for maintenance |
| $C^*$ | Proportion of arriving subassemblies which branches, at a branch node, to the path intended either for defective units or for maintenance |
| D | Proportion of arriving defective units which branches, at a branch node, to the path intended either for defective units or for maintenance |
| E | Proportion of arriving good units which branches, at a branch node, to the path intended either for defective units or for maintenance |
| G | Representative age at which the majority of units arriving at a branch node branches to the path intended either for defective units or for maintenance, years |
| K | Number of components in identifiable or distinguishable assembly or subassembly |
| K\$ | Denotes components which belong to an identifiable assembly or subassembly at a node |
| N | Number of units in path |
| Q | Quality (proportion defective) of units in path |
| $\alpha$ | Weibull characteristic life, years |
| $\beta$ | Weibull slope or shape parameter |
| $\pi$ | Denotes multiplication (e.g., $\prod_3 X_i = X_1 \cdot X_2 \cdot X_3$) |
| $\triangledown$S | On schematic diagram, denotes flow of scrapped units |
| $\triangle$R | On schematic diagram, denotes flow of replacement units |
| Subscript k | Denotes component number |
| Subscript 1 or 2 | Denotes path (1 = path intended either for defective units or for maintenance, 2 = path intended either for good units or for units not requiring maintenance) |

## 1. INTRODUCTION

The high speed passenger train truck is required to perform a large variety of tasks. These tasks include supporting and guiding the car, generating the braking (and, frequently, the traction) forces, and providing an acceptable ride to the passengers. Because the truck has so many functions, it is a complex electromechanical system with many interrelated components. The truck is consequently expensive to purchase and can be expensive to maintain.

A purchaser of a set of high speed passenger train trucks can determine relatively easily the initial purchase cost. It is much more difficult, however, to determine how much his truck fleet will cost to maintain. The maintenance cost problem is made especially difficult by factors such as the following:

- The maintenance cost is influenced by the maintenance policies and procedures of the user as well as by the design of the truck. The cost is also influenced by the type of service required of the truck.
- The maintenance cost for a subassembly or component can be influenced by the other subassemblies and components in the truck.
- The maintenance cost is produced by a combination of planned servicings as well as by unplanned occurrences. The unplanned occurrences are statistical in nature because they cannot be predicted precisely.
- The most important maintenance cost areas and components may be difficult to identify and the maintenance cost associated with these may not be known.
- The maintenance cost typically will vary with time even for a given use and set of trucks.

The difficulties associated with assessing the maintenance costs of a large set of trucks motivates the development of an overall economic maintainability model. This methodology must incorporate, at the very least, those factors which strongly influence any part of the truck cost or usage characteristics. This report presents such a methodology. The methodology -- the simulation cost model (SCM) -- is a consistent quantitative technique which provides

- the annual total maintenance cost and breakdown of this cost
- a qualitative and quantitative description of the maintenance operation
- a means of evaluating alternative designs and the economic effect of specifications
- a means of estimating transient (time dependent) maintenance costs and maintenance operations
- identification of the data which are required in applying the technique (these data requirements are generally compatible with those data typically available in the industry)

The simulation cost modelling technique was first developed under Contract DOT/TSC 917, which was concerned with railroad roller bearing certification and diagnostics. In that work [1] - [2],* a single-component version of the model was used to estimate annual bearing operating costs and to consider the cost/benefit effects of certain diagnostic procedures. The model developed under that contract was subsequently generalized during work under Task VIII of Phase II of the Track Train Dynamics (TTD) Program. In that generalization [3] - [5], the capability to treat the presence of defective

*Numbers in brackets denote references (Appendix F) units was added to the model. Another feature was also added. That feature allowed the computer program of the SCM to be independent of the particular component and maintenance system being considered. During the TTD work, the program was applied to freight car roller bearings, wheels, side frames, and bolsters.

The SCM described in the present report represents a further generalization of the technique. This generalization primarily involves adding the capability to consider many components simultaneously. The resulting SCM is then applied to the trucks of two present-day high speed trains: the Metroliner and the Amcoach.

The present report is intended

- o to review the high speed trucks which are candidates for the maintenance methodology
- o to present the SCM methodology
- o to describe the application of the SCM to the Metroliner (powered) and Amcoach (unpowered) trucks
- o to show the type of results available from the SCM, and
- o to indicate how such results can be used.

Review of the high speed trucks is considered in Section 2. That section is subdivided into 3 subsections as follows:

2.1 Literature Search

2.2 Design Analysis

2.3 Operational Framework

The literature search is intended to identify all existing and near-term passenger train trucks which are suitable for consideration by the SCM. Only those few trucks capable of providing acceptable ride quality for modern lightweight rolling stock at speeds of at least 125 mph are relevant. From the search, 41 trucks were identified. The literature search is also intended to categorize those relevant trucks in terms of generic design concepts. The resulting characterizations are given in tabular form. The literature search indicated that little published data exist which are directly useful for the SCM.

The design analysis is intended to identify, with respect to each relevant truck, the factors for which data are required. This identification process is influenced to a considerable extent by the requirements of the maintainability methodology being used. For the SCM technique, the data requirements evolve naturally from a schematic diagram which describes the maintenance of the truck. As a result, this subsection characterizes each relevant truck to determine the nature of its maintenance requirements. This characterization is in the form of tables. The characterization, together with the operational framework, can then be used to generate the schematic diagram.

The operational framework is intended to provide the operational and maintenance conditions for the trucks. The contents of the operational framework are also influence by the requirements of the maintainability methodology. For the simulation technique, the operational framework is a description of how the operating system (i.e., the railroad) acts to maintain its trucks. This qualitative description is in the form of a figure. The figure, together with the maintenance evaluation of the design analysis, can then be used to generate the schematic diagram.

In Section 3. of the report, the SCM technique is described. The description is given in terms of two of the major components of the technique -- the schematic diagram and the computer program. The section presents and defines the SCM parameters for which values need be obtained. The section also presents an analytical background sufficient for a basic understanding of the technique. At the end of the section, those schematic diagrams used for the Metroliner and Amcoach trucks are given.

Section 4. of the report discusses and presents the data used for trucks. These data are identified in large part by the schematic diagram. The data include maintenance intervals, operation practices, unit costs, etc. The section includes a general discussion and a detailed description of how the values of the SCM decision parameters are obtained from the available data. The section also includes the resulting values for these parameters. At the end of the section, the base case analysis for each truck is given. This base case analysis is a description of the current (present time) maintenance costs and truck maintenance actions.

The base case analysis forms the reference for sensitivity analyses (effects on truck maintenance costs and operations produced by changes in the base case) and for simulations (projections of truck maintenance costs and operations). These sensitivity analyses and simulations are considered in Section 5. That section also describes how the sensitivity analyses are used and presents examples. In that context, the section treats the topic of truck specifications and how such specifications are related to the SCM technique.

Conclusions and recommendations are given in Section 6.

Several appendices are included in the report. Appendix A gives the BASIC program listing for the SCM and discusses how the program is employed by a user. Appendix B describes the maintenance and data records for the Amcoach fleet. Appendix C contains data obtained from the Canadian National Railroad for the Turbotrain truck. Appendix D lists areas appropriate to truck specifications and features which may be desirable in such specifications. Appendix E is the report of inventions statement, and includes a brief discussion of areas of SCM applicability. Appendices F and G give, respectively, the references and bibliography for this work.

## 2. SURVEY AND ANALYSIS OF TRUCK TECHNOLOGY AND USAGE

### 2.1 Literature Search

The literature search consisted of two parts -- a search of published literature and a manufacturer survey.

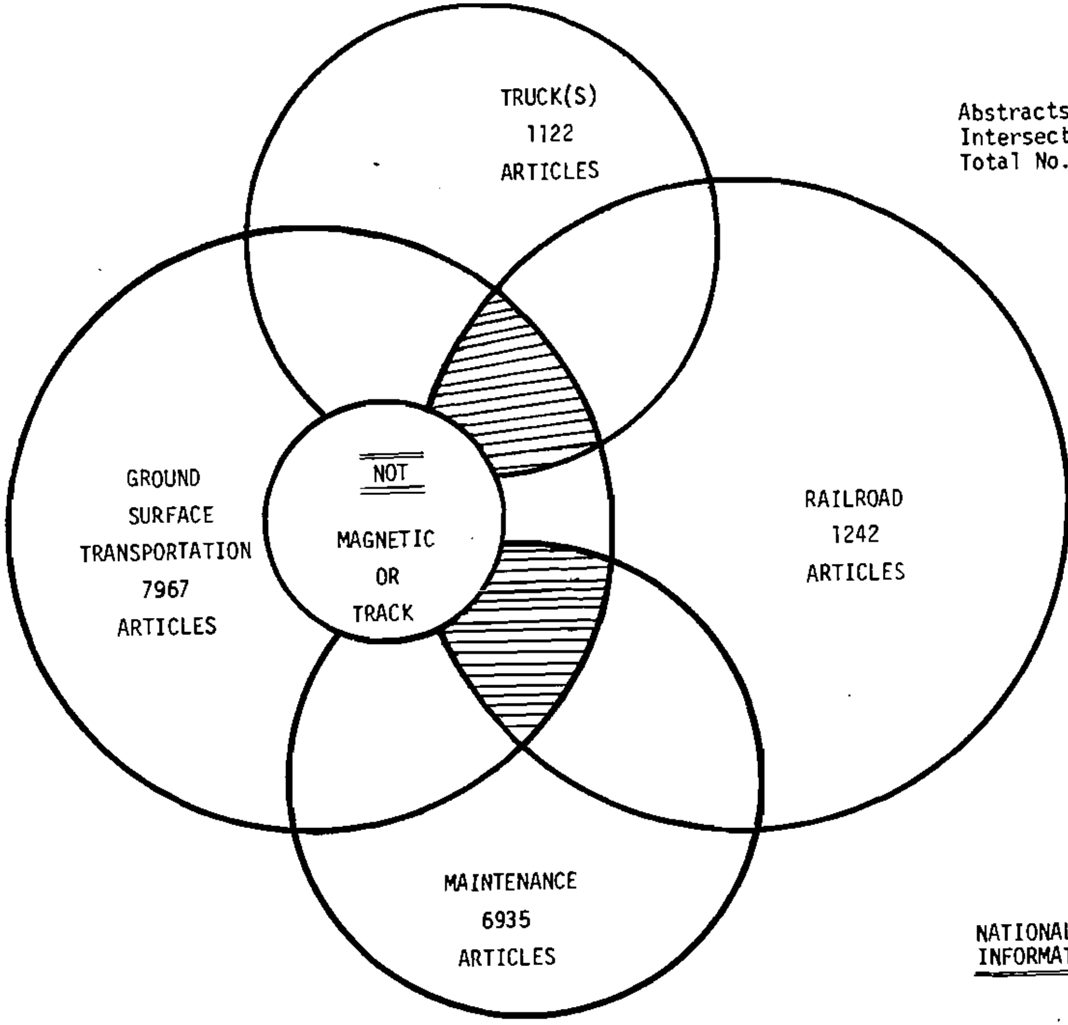
The search of published literature involved the aid of

- o The Railroad Research Information Service (RRIS) Bulletins
- o Two Computerized Indexes
  - The National Technical Information Service (NTIS)
  - The Engineering Index (EI)
- o The Budd Company

The RRIS Bulletins (and manufacturer's literature) produced a list of 38 companies related to truck and/or truck component design. The Bulletins also produced a number of papers which described several high speed trucks or dealt with the area of truck economics. More papers of these types were uncovered from the computerized searches. These searches are shown schematically in Figures 2.1 and 2.2.

Figure 2.1 describes the NTIS search. The NTIS files contain over 560,000 abstracts from the beginning of 1964. Figure 2.2 describes the EI search. The EI files contain more than 412,000 abstracts from the beginning of 1970. The distribution of these abstracts among topics of some interest to the present program is indicated in the figures. The shaded regions in the figures indicate those abstracts which are potentially applicable to the work.

The computer searches showed that the shaded regions contained approximately 128 abstracts. A list of subjects of these abstracts and those from the RRIS is given in Table 1.1. Of the NTIS and EI abstracts, 21 appeared to be of immediate interest to the program. These 21 articles were produced for further review. A list of these procured papers and those produced from the RRIS Bulletin is given in the Bibliography (Appendix G).

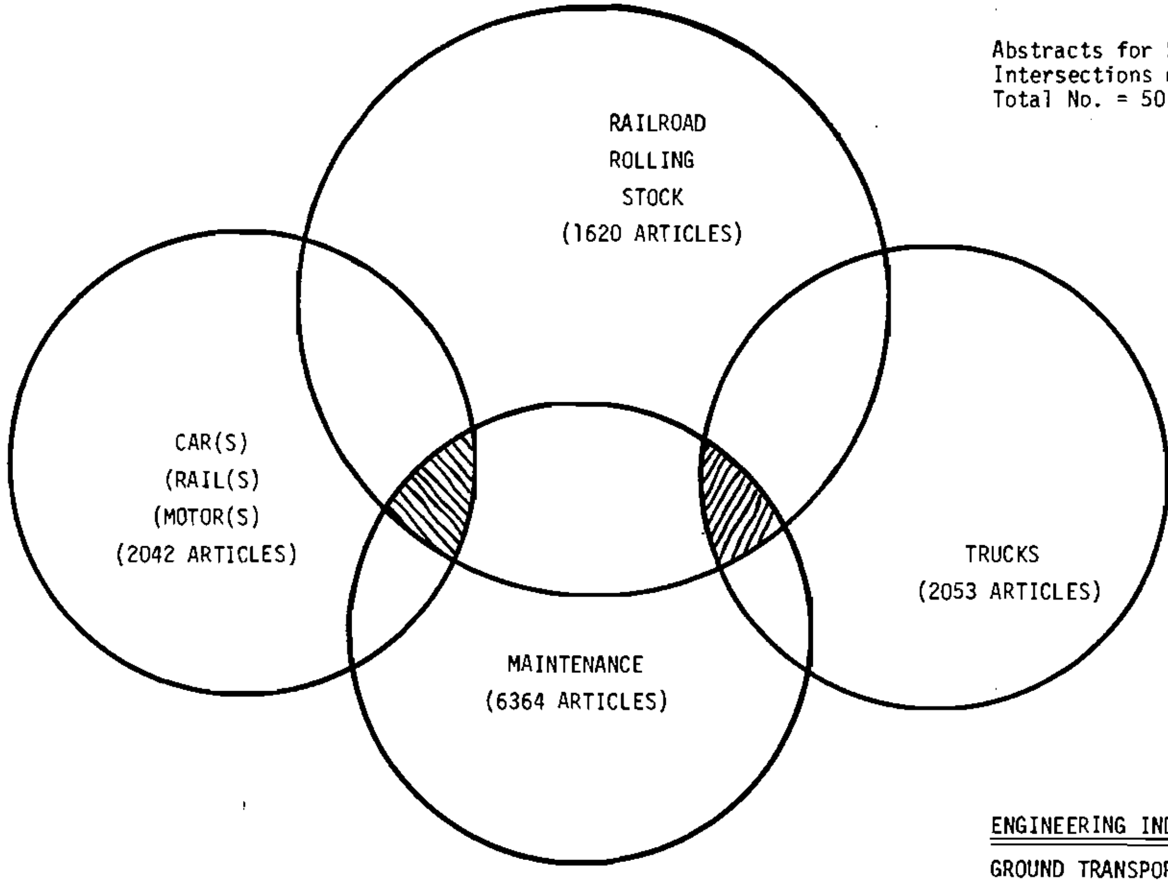



Abstracts For Shaded
Intersections on Order
Total No. = 78 Articles

NATIONAL TECHNICAL
INFORMATION SERVICE

FIGURE 2.1 VENN DIAGRAM OF KEY WORDS USED IN COMPUTER SEARCH

Abstracts for Shaded
Intersections on Order
Total No. = 50 Articles




ENGINEERING INDEX

GROUND TRANSPORTATION
FILE

FIGURE 2.2 VENN DIAGRAM OF KEY WORDS USED IN COMPUTER SEARCH

TABLE 2.1

LITERATURE SEARCH DISTRIBUTION RESULTS

| | Description of Related Subject | Number of Articles |
|---|---|---|
| 1. | Train Truck Related | 13 |
| 2. | Economic | 12 |
| 3. | Design Studies (including TDOP)* | 40 |
| 4. | High Speed Vehicles (plus SOAC)** | 13 |
| 5. | Instrumentation | 8 |
| 6. | Vehicle Subassemblies (springs/couplers/bearings/ wheels) | 13 |
| 7. | System Maintenance | 4 |
| 8. | Freight Train | 4 |
| 9. | Locomotives | 2 |
| 10. | Miscellaneous not applicable to this study | 42 |
| | Total: | 151 |

* Truck Design Optimization Project

** State of the Art Car

The Budd Company has produced a report [6] on the dynamic characteristics of high speed trucks. That report and discussions with Budd personnel produced some of the trucks identified for the present work.

The manufacturer survey involved sending a letter of inquiry to the companies mentioned above. A copy of that letter is given as Figure 2.3. Approximately one-third of the companies responded. A summary list of these responses is given in Table 2.2. Nine companies indicated that they manufacture high speed trucks.

The results of the literature search indicated that there is little published maintenance data which are directly useful for the simulation cost model. The results did produce a list of 41 trucks* which could have been considered under the contract. These trucks and certain information concerning the trucks are listed in Tables 2.3a - 2.3d.

Tables 2.3a - 2.3d have been developed such that they characterize the trucks in terms of their generic design concepts. Each truck is given by a row in the tables. The columns of the tables give the important features of the truck. The columns show the country of origin, the manufacturer or user, the maximum design speed, whether the truck is in revenue service, indications of any special truck features, and descriptions of the characteristics of its major subsystems. These subsystems are the propulsion system, the wheel sets, the primary suspension, the braking system and the secondary suspension.

Due to time and budgetary constraints, definitive information for each truck/column combination could not be obtained. As a result, many of the entries in the table are to some extent uncertain. Such entries are so

---

*Complete as of April 15, 1977.

SUBJECT: SALES LITERATURE PERTAINING TO HIGH SPEED RAILWAY TRUCKS

Gentlemen:

We are seeking to identify all manufacturers of high speed passenger railway trucks. If you design, build, and/or sell railway trucks capable of operation at 125 MPH (200 KM/HR) or greater, please indicate this to us so that we add your company to our list of potential sources.

We would also appreciate sales literature identifying your rail truck systems and the address of your nearest distributor.

Thank you for your cooperation.

Very truly yours,

FIGURE 2.3 LETTER OF INQUIRY

TABLE 2.2

COMPANIES RESPONDING TO SURVEY
(As of April 15, 1977)

| COMPANY NAME | RESPONSE L = LETTER P = PHONED | TRUCK DESIGNATION | MANUFACTURES HIGH SPEED DESIGN | DESIGN SPEED KM/HR/MPH | LITERATURE RECEIVED | COMMENTS |
|---|---|---|---|---|---|---|
| British Rail Engineers | L | Apt | Yes | 250/155 | Yes | Development Stages |
| DGA International | L | Y-32<br>Y-226 | Yes<br>Yes | 250/155<br>280/174 | Yes<br>Yes | |
| GSI (Buckeye Steel) | L | GSI | Yes | 200/125 | Yes | Response from GSI |
| M.A.N. | L | ET-403 | Yes | 200/125 | | |
| Nippon Sharyo | L | None | Yes | 286/178 | Yes | |
| Standard Car | L | None | Yes | 200/125 | No | Freight - New Design Not Marketed Yet |
| SIG | L | None | Yes | 200/125(?) | Yes | |
| Midland-Ross | L | None | No | None | None | |
| Rockwell International | L | None | No | None | None | |
| Rohr | L | None | No | None | None | |
| Scullin | L | None | No | None | None | |
| Westinghouse | L | None | No | None | None | |
| Adirondack Steel | P | None | Maybe | None | None | Referred Us to GE Locomotive |
| AiResearch (Garret) | L | None | No | None | None | Prime Contractor Only<br>Suggests: Boeing Vertol<br>Urban Development<br>Hawker-Siddeley<br>Societe Franco |

TABLE 2.3a

HIGH SPEED TRUCK CHARACTERISTICS
(Symbols defined at end of table)

| TRUCK ID No. | TRUCK OR VEHICLE DESIGNATION | COUNTRY | MANUFACTURER (M) OR USER (U) | MAXIMUM DESIGN SPEED MPH (km/h) | IN REVENUE SERVICE | SPECIAL FEATURE |
|---|---|---|---|---|---|---|
| 1 | LRC Passenger Bogie | Canada | Dominion Foundries and Steel Ltd. (M) (DOFASCO) | 120 (193) | - | Active Tilt Control |
| 2 | LRC Locomotive Bogie | Canada | DOFASCO (M) | 120 (193) | - | Secondary Suspension Bellows Air Spring in Parallel with Coil |
| 3 | BT10 | England | British Railways (U) Passenger Bogies for High Speed Train (HST) | 143 (230) | X | Swing Hanger |
| 4 | HST Locomotive Bogie | England | British Railways (U) | 143 (230) | X | |
| 5 | APT-E Passenger Bogie | England | British Railways (U) | 155 (250) | - | Long Bolster Swinging Arms |
| 6 | APT-E Locomotive Bogie | England | British Railways (U) | 155 (250) | - | Advanced Secondary Suspension |
| 7 | APT (BT12) End Trailer Bogie | England | British Railways (U) | 155 (250) | - | Active Tilt Control |
| 8 | APT (BT11) Intermediate Bogie | England | British Railways (U) | 155 (250) | - | Active Tilt Control Articulation Bogie |
| 9 | APT (BT17) Locomotive Trucks | England | British Railways (U) | 155 (250) | - | |

Table 2.3a (continued)
(Symbols defined at end of table)

| TRUCK ID NO. | TRUCK OR VEHICLE DESIGNATION | COUNTRY | MANUFACTURER (M) OR USER (U) | MAXIMUM DESIGN SPEED MPH (km/h) | IN REVENUE SERVICE | SPECIAL FEATURE |
|---|---|---|---|---|---|---|
| 10 | Y-28 | France | SNCF (U) (French National Railways) | 125 (200) | X | Traction Linkages |
| 11 | Y-32 | France | SNCF (U) | 155 (250) | X | Traction Linkages |
| 12 | Y-223 | France | SNCF (U) | 125 (200) | X | |
| 13 | Y-224 | France | SNCF (U) | 125 (200) | X | |
| 14 | Y-225 | France | SNCF (U) | 186 (300) | - | Articulated Train Radius Arm Primary |
| 15 | Y-226 | France | SNCF (U) | 174 (280) | - | Body Suspended Motors |
| 16 | CC6500 | France | SNCF (U) Alsthom-MTE (M) | 140 (225) | X | |
| 17 | CC7100 | France | SNCF (U) | 125 (200) | X | |
| 18 | CC21000 | France | SNCF (U) Alsthom-MTE (M) | 140 (225) | X | |
| 19 | CC40100 | France | SNCF (U) Alsthom (M) | 150 (240) | X | |

Table 2.3a (continued)
(Symbols defined at end of table)

| TRUCK ID No. | TRUCK OR VEHICLE DESIGNATION | COUNTRY | MANUFACTURER (M) OR USER (U) | MAXIMUM DESIGN SPEED MPH (km/h) | IN REVENUE SERVICE | SPECIAL FEATURE |
|---|---|---|---|---|---|---|
| 20 | ET403 | Germany | MAN (M) | 125 (200) | X | Bolsterless |
| 21 | Minden Deutz | Germany | Klockner Humboldt Deutz (M) | 155 (250) | x | Swing Hanger |
| 22 | E103 | Germany | Henschel (M) | 125 (200) | X | |
| 23 | E103-110 | Germany | Henchel (M) | 155 (250) | X | Pivotless Lightweight Bogie |
| 24 | Fiat Eurofa | Italy | FIAT (M) | 155 (250) | X | |
| 25 | Z1040 | Italy | BREDA (M) | 125 (200) | X | Swing Hanger |
| 26 | Y 0160 | Italy | FIAT (M) | 155 (250) | X | Body Suspended Motors, Tilt Control |
| 27 | E444 | Italy | Italian Railways (U) | 125 (200) | X | Swing Hanger 2 Axles |
| 28 | E666 | Italy | Italian Railways (U) | 125 (200) | X* | 3 Axles |
| 29 | DT200 | Japan | JNR (U) | 130 (210) | X | |
| 30 | 951 Experimental | Japan | Shinkansen (U) | 161 (260) | - | |
| 31 | 961 | Japan | Shinkansen (U) | 161 (260) | X* | |

Table 2.3a (continued)

| TRUCK ID No. | TRUCK OR VEHICLE DESIGNATION | COUNTRY | MANUFACTURER (M) OR USER (U) | MAXIMUM DESIGN SPEED MPH (km/h) | IN REVENUE SERVICE | SPECIAL FEATURE |
|---|---|---|---|---|---|---|
| 32 | Rc4 | Sweden | Asea (M) | 120 (193) | X | |
| 33 | Improved Metroliner | Switzer-land | LTV/SIG (M) | 160 (258) | - | Bell Crank Primary |
| 34 | P-III | U.S. | Budd (M) | 120 (193) | X | Articulated |
| 35 | Metroliner | U.S. | GSI (M) | 125 (200) | X | Equalizer Beam |
| 36 | E-60 | U.S. | General Electric (M) | 120 (193) | X | |
| 37 | UAC Single Axle | U.S. | United Aircraft (M) Canadian National Railroad (U) (CNR) | 160 (258) | X | Single Axle Truck |
| 38 | UAC Double Axle | U.S. | United Aircraft (M) CNR (U) | 160 (258) | X | Articulated Truck |
| 39 | AMT-125 | U.S. | General Motors (M) | 125 (200) | | |
| 40 | Department of Commerce Test Cars | U.S. | Budd (M) | 160 (258) | - | Articulated Truck |
| 41 | ER200 | USSR | Soviet Railways (U) | 125 (200) | X | |

(blank) Denotes that information is very uncertain or is not available

X Denotes that characteristic applies to truck

\- Denotes that characteristic does not apply to truck

X* Denotes some uncertainty in applicability of characteristic to truck

TABLE 2.3b

HIGH SPEED TRUCK CHARACTERISTICS

(Symbols defined at end of table)

| TRUCK ID No. | PROPULSION: POWERED | PROPULSION: UNPOWERED | PROPULSION: LOCOMOTIVE | COMMENTS ON PROPULSION | WHEEL SETS: SOLID STEEL WHEELS | AXLES: SOLID AXLES | AXLES: HOLLOW AXLES | JOURNAL BEARINGS: INBOARD BEARINGS | JOURNAL BEARINGS: OUTBOARD BEARINGS |
|---|---|---|---|---|---|---|---|---|---|
| 1 | - | X | - | | X | X | - | X | - |
| 2 | - | - | X | G.E. No. 752 Direct Current Axle Hung | X | X* | - | - | X |
| 3 | - | X | - | | X | X | - | - | X |
| 4 | - | - | X | Frame Mounted Traction Motors | X* | - | X | - | X |
| 5 | - | X | - | | X | - | X | - | X |
| 6 | - | - | X | Two AEI Motors (253 AY) | X | X* | - | - | X |
| 7 | - | X | - | | X | - | X | - | X |
| 8 | - | X | - | | X | - | X | - | X |
| 9 | - | - | X | | X | X* | - | - | X |
| 10 | - | X | - | | X* | X* | - | - | X |
| 11 | - | X | - | | X* | X* | - | - | X |
| 12 | X | - | - | | X | X | - | - | X |
| 13 | - | X | - | | X | X | - | - | X |
| 14 | X | - | - | TAO 670 Direct Current | X | X* | - | - | X |

Table 2.3b (continued)
(Symbols defined at end of table)

| TRUCK ID No. | PROPULSION: POWERED | UNPOWERED | LOCOMOTIVE | COMMENTS ON PROPULSION | WHEEL SETS: SOLID STEEL WHEELS | AXLES: SOLID AXLES | HOLLOW AXLES | JOURNAL BEARINGS: INBOARD BEARINGS | OUTBOARD BEARINGS |
|---|---|---|---|---|---|---|---|---|---|
| 15 | Body Suspended Motors | - | - | TAO 670 Direct Current | X* | X* | - | - | X |
| 16 | - | - | X | Single Motor Truck (2 gear ratios) | X* | X* | - | - | X |
| 17 | - | - | X | | X* | X* | - | - | X |
| 18 | - | - | X | Single Motor Truck (2 gear ratios) | X | X | - | - | X |
| 19 | - | - | X | Single Motor Truck (2 gear ratios) | X* | X* | - | - | X |
| 20 | X | - | - | | X | X | - | - | X |
| 21 | - | X | - | | X | X | - | - | X |
| 22 | - | - | X | | X | X | - | - | X |
| 23 | - | - | X | Brushless Traction Motors 3 Axle Truck with one Motor per Axle | X | X | - | - | X |
| 24 | - | X | - | | X | X | - | - | X |
| 25 | X | - | - | | X | X | - | - | X |

Table 2.3b (continued)
(Symbols defined at end of table)

| TRUCK ID No. | PROPULSION: POWERED | PROPULSION: UNPOWERED | PROPULSION: LOCOMOTIVE | PROPULSION: COMMENTS ON PROPULSION | WHEEL SETS: SOLID STEEL WHEELS | WHEEL SETS: AXLES: SOLID AXLES | WHEEL SETS: AXLES: HOLLOW AXLES | WHEEL SETS: JOURNAL BEARINGS: INBOARD BEARINGS | WHEEL SETS: JOURNAL BEARINGS: OUTBOARD BEARINGS |
|---|---|---|---|---|---|---|---|---|---|
| 26 | Body Suspended Motors | - | - | | X* | X* | - | - | X |
| 27 | - | - | X | Frame Suspended | X | X | - | - | X |
| 28 | - | - | X | T750 Type | X | X | - | - | X |
| 29 | X | - | - | | X | X | - | - | X |
| 30 | X | - | - | | X | X | - | - | X |
| 31 | X | - | - | 275 kw Motors one per Axle Mounted on Bogie Frame | X | X | - | - | X |
| 32 | - | - | X | | X* | X* | - | | |
| 33 | X | - | - | 2 Traction Motors (Westinghouse or G.E.) | X | X | - | - | X |
| 34 | - | X | - | | X | X | - | X | - |
| 35 | X | - | - | Westinghouse & G.E. Traction Motors | X | X | - | - | X |
| 36 | - | - | X | | X | X | - | - | X |
| 37 | - | X | - | | X | X | - | X | - |

Table 2.3b (continued)

| TRUCK ID. NO. | PROPULSION: POWERED | UNPOWERED | LOCOMOTIVE | COMMENTS ON PROPULSION | WHEEL SETS: SOLID STEEL WHEELS | AXLES: SOLID AXLES | HOLLOW AXLES | JOURNAL BEARINGS: INBOARD BEARINGS | OUTBOARD BEARINGS |
|---|---|---|---|---|---|---|---|---|---|
| 38 | X | - | - | 2 Axle Hung Motors per Truck | X | X | - | X | - |
| 39 | | | | | | | | | |
| 40 | X | - | - | 2 G.E. Traction Motors Per Truck | X | - | X | X | - |
| 41 | X | - | - | | X | X | - | - | X |



(blank) Denotes that information is very uncertain or is not available

X Denotes that characteristic applies to truck

\- Denotes that characteristic does not apply to truck

X* Denotes some uncertainty in applicability of characteristic to truck

TABLE 2.3c

HIGH SPEED TRUCK CHARACTERISTICS
(Symbols defined at end of table)

| TRUCK ID NO. | COIL SPRING | RUBBER | LEAF LINKS | SOFT (LOW VERTICAL STIFFNESS) | OTHER | DAMPERS | DYNAMIC | INBOARD | OUTBOARD | TREAD | EDDY CURRENT | TRACK | OTHER |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | PRIMARY SUSPENSION | | | | | | BRAKES | | | | | | |
| 1 | - | X | - | X | - | X | - | X | - | X* | - | | |
| 2 | - | X | - | X* | - | X* | X | - | - | X | - | | |
| 3 | X | - | - | X | Radius Arm | X | - | Wheel Mounted Disks | | - | - | | |
| 4 | X | X | - | X* | - | X | X | X* | X* | - | | | |
| 5 | X | - | - | X* | - | X | - | - | - | X | - | | Hydro-kinetic |
| 6 | X | X | - | X* | - | X | X | | | X* | | | |
| 7 | X | X | - | | | X | | | | | | | Hydro-kinetic |
| 8 | X | X | - | X* | | X | | | | | | | Hydro-kinetic |
| 9 | X | X | - | X* | | X | | | | | | | |
| 10 | X | X | - | X | - | - | - | - | - | X | - | X | - |
| 11 | X | X | - | X | - | X | - | X | - | X | - | X | - |
| 12 | X | X | - | X | - | X* | X | - | - | X | - | X | - |
| 13 | X | X | - | X | - | X | - | X | - | X | - | X | - |
| 14 | X | X | - | X | - | X | X | - | - | X | X | X | - |
| 15 | X | X | - | X | - | X | - | - | - | X | X | - | - |
| 16 | X | | - | X* | | | X* | - | - | X | - | | |
| 17 | X | | - | X* | | | X* | - | - | X* | - | | |

Table 2.3c (continued)
(Symbols defined at end of table)

| TRUCK ID NO. | PRIMARY SUSPENSION: COIL SPRING | RUBBER | LEAF LINKS | SOFT (LOW VERTICAL STIFFNESS) | OTHER | DAMPERS | BRAKES: DYNAMIC | INBOARD | OUTBOARD | TREAD | EDDY CURRENT | TRACK | OTHER |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 18 | X | | - | X* | | X | X* | - | - | X | - | | |
| 19 | X | | - | X* | | | X* | - | - | X | - | | |
| 20 | X | | X | X | - | X | X* | Wheel Mounted Disks | | X* | - | X | - |
| 21 | X | | X | X | - | X | - | X* | X* | X | - | X* | - |
| 22 | X | X* | - | X* | | X | X* | - | - | X* | - | | |
| 23 | X | X* | - | X* | | X | X* | - | - | X* | - | | |
| 24 | X | X | - | X | - | X | - | X | - | X | - | X | - |
| 25 | X | X | - | X | - | Friction Damper | X | - | - | X | - | - | - |
| 26 | X | X | - | X* | - | X* | X* | X | - | X* | - | X | |
| 27 | X | X | - | X* | - | | X | - | - | X | - | | |
| 28 | X | | - | X* | - | | X | - | - | X* | - | | |
| 29 | X | - | X | X | - | X | X | X* | X* | X | - | | - |
| 30 | X | - | X | X* | - | X | X | X* | X* | | - | | |
| 31 | X | - | X | X* | - | X | X | X* | X* | | - | | |
| 32 | | | | | | | | | | | | | |
| 33 | X | - | - | X | Bell Crank | X | X | Wheel Mounted Discs | | X | - | | |

Table 2.3c (continued)

| TRUCK ID NO. | PRIMARY SUSPENSION: COIL SPRING | RUBBER | LEAF LINKS | SOFT (LOW VERTICAL STIFFNESS) | OTHER | DAMPERS | BRAKES: DYNAMIC | INBOARD | OUTBOARD | TREAD | EDDY CURRENT | TRACK | OTHER |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 34 | - | X | - | - | Side Bearings | - | - | X | - | - | - | - | Handbrake |
| 35 | - | - | - | - | Pirelli | Pedestal Liner | X | - | - | X | - | - | - |
| 36 | X | | - | X* | | X | | | | | | | |
| 37 | - | X | - | X* | | | - | - | - | X | - | - | - |
| 38 | - | X | - | X* | | | X* | - | - | X | - | - | - |
| 39 | | | - | | | | | | | | | | |
| 40 | - | X | - | - | Side Bearings | | X | - | - | X | - | - | - |
| 41 | X | X | - | X | - | X | X | Wheel Mounted Discs | | X | - | X | |

(blank) Denotes that information is very uncertain or is not available

X Denotes that characteristic applies to truck

\- Denotes that characteristic does not apply to truck

X* Denotes some uncertainty in applicability of characteristic to truck

TABLE 2.3d

HIGH SPEED TRUCK CHARACTERISTICS

(Symbols defined at end of table)

| TRUCK ID NO. | SECONDARY SUSPENSION COIL | RUBBER | AIR | OTHER | DAMPERS | ANCHOR RODS | LEVELING VALVE | CENTER PLATE WEAR PADS | COMMENTS |
|---|---|---|---|---|---|---|---|---|---|
| 1 | - | X | X | - | X | - | X* | | |
| 2 | X | - | X | - | X | - | X* | X* | |
| 3 | - | | X | Swing Links | X | X | X | | |
| 4 | X | | - | - | X | - | - | | Secondary Yaw Damping |
| 5 | - | - | - | Hydraulic Jacks with Nitrogen Accumulators | | - | X | | 2 Main Truck Frames with Intermediate Frame |
| 6 | - | | X | Swing Links | X | X | X | | |
| 7 | - | | X | Roll Bar | X | X | X* | | |
| 8 | - | | X | Independent Secondary Suspension Roll Bar | X | X | X* | | |
| 9 | X | | | | X | X | | | |
| 10 | X | - | - | Swing Links Roll Bar | X | - | - | | |
| 11 | X | - | - | Roll Bar | X | - | - | | Secondary Yaw Damping |

Table 2.3d (continued)
(Symbols defined at end of table)

SECONDARY SUSPENSION

| TRUCK ID NO. | COIL | RUBBER | AIR | OTHER | DAMPERS | ANCHOR RODS | LEVELING VALVE | CENTER PLATE WEAR PADS | COMMENTS |
|---|---|---|---|---|---|---|---|---|---|
| 12 | X | X | - | - | X | - | - | | |
| 13 | X | X | - | - | X | - | - | | |
| 14 | | X | X | - | X | - | X | | Secondary Yaw Damping |
| 15 | X | X | - | - | X | - | - | | Secondary Yaw Damping |
| 16 | - | X | - | | X | | - | | |
| 17 | | X* | | | X* | | | | |
| 18 | | X | | | X* | | | | |
| 19 | | X | | | X* | | | | |
| 20 | - | X | X | | X | - | X | | |
| 21 | X | - | - | Swing Links | X | - | - | | |
| 22 | X | | | | X | | | | |
| 23 | X | | | | X | | | | |
| 24 | X | X | - | Roll Bar | X | - | - | | Secondary Yaw Damping |
| 25 | X | - | - | Swing Links | X | - | - | | Slide Pad |
| 26 | X | | | | X | - | | | Articulated Frame |
| 27 | X | | - | Swing Links | X | | - | | |

Table 2.3d (continued)

SECONDARY SUSPENSION

| TRUCK ID NO. | COIL | RUBBER | AIR | OTHER | DAMPERS | ANCHOR RODS | LEVELING VALVE | CENTER PLATE WEAR PADS | COMMENTS |
|---|---|---|---|---|---|---|---|---|---|
| 28 | - | X | - | | X* | | - | | |
| 29 | - | - | X | - | X | X | X* | | |
| 30 | - | | X | - | X | X | X* | | |
| 31 | - | | X | - | X | X* | X* | | |
| 32 | | | | | | | | | |
| 33 | - | X | X | - | X | X | X | | |
| 34 | X | - | X | Lateral Stabilizing Rods | X | X | X | X | |
| 35 | X | - | X | | X | X | X | X | |
| 36 | X | | | | X | | | | |
| 37 | - | | X | | | | X* | | |
| 38 | - | | X | | | | X* | | |
| 39 | | | | | | | | | |
| 40 | - | - | X | - | X | X | X | X | |
| 41 | - | | X | | X | X | X* | | |

(blank) Denotes that information is very uncertain or is not available

\- Denotes that characteristic does not apply to truck

X Denotes that characteristic applies to truck

X* Denotes some uncertainty in applicability of characteristic to truck

indicated by the symbols used for the table. The set of table symbols and their definitions is given at the end of each of the tables.

The tables indicate that there is a considerable variation in the design of the high speed trucks. This variation exists primarily in the suspension arrangements, in the type of braking used, and the location of the wheels with respect to the bearings. Such differences among the trucks are reflected in their maintenance requirements as shown below.

## 2.2 Design Analysis

The intent of the design analysis and of the operational framework (Section 2.3) is to provide information sufficient to produce a schematic diagram. In this section, the maintenance requirements of the truck are developed. In the next section, the maintenance actions of the operating system (the railroad) are developed. The schematic diagram for each truck-railroad combination is then a description of how a particular railroad operates a particular truck.

There is, in general, one schematic diagram for each truck-railroad combination. However, if the maintenance for one truck as used by a railroad is the same as that for another truck as used by that (or by another) railroad, then the same schematic diagram can be used for both truck-railroad combinations. Consequently, the trucks are characterized to reveal similar maintenance requirements for trucks which may not appear to have much similarity.

The characterization of the trucks in terms of their maintenance requirements is, as above, accomplished by using a tabular format. Each truck for which sufficient information was available was considered in terms of its components and in terms of several maintenance subjects. The result for each truck is a table which describes the sequence of actions necessary to inspect and to service each of its components. The table for each truck also identifies the major subassemblies to which each component belongs, the typical defect modes for the component, and whether the component is repairable. Tables for 17 of the 41 trucks were produced. In these tables, the columns refer to the components of the truck--the definitions of the component numbers are given in Table 2.4. The rows describe the maintenance subjects considered--definitions of these subjects are given in Table 2.5. The entries in the tables are defined at the bottom of Table 2.4.

The maintenance categorization tables are given as Tables 2.6 through 2.22.

An example can be used to show how the tables define the maintenance actions for a truck. Considering the Metroliner Table (Table 2.21) and component 7 (wheels), it can be seen from Row 1 that the wheel is part of subassemblies B and C. From Row 2, none of these subassemblies need be removed from the car to inspect the wheel. From Row 3, none of the components in subassembly C need to be removed for inspection of the wheel. Row 4 indicates that, to service the wheel, subassembly B must be removed from the car and subassembly C must be removed from subassembly B. Row 5 shows that, for major service (i.e., replacement) of the wheel, the bearing and the wheel have to be removed from subassembly C. Typical defect modes as listed in Row 6 are wear, fatigue, and broken. Row 7 shows that it is possible to repair a defective wheel (e.g., by turning) so that the complete set of actions culminating in wheel removal may not be necessary.

All of the components of interest for the present work are considered in the maintenance categorization tables. Therefore, if the maintenance policy (i.e., the operational framework) of the railroad which operates the truck is known, the tables and the policy together define the way the truck is maintained. Sufficient information then exists to construct the schematic diagrams of Section 3.

## 2.3 Operational Framework

The operational framework was, for the purposes of this report, taken to be that which describes the Amtrak system. The rationale for this is that the simulation technique typically will be applied to Amtrak's use of any of the trucks given in Section 2.1. Therefore, the generation of an operational framework for another railroad does not seem to be warranted, even though that framework may differ only slightly from that for Amtrak.

TABLE 2.4

COMPONENT NUMBER DESCRIPTIONS AND TERMINOLOGY

| | |
|---|---|
| 1 | Primary Springs |
| 2 | Secondary Springs (Coil or Air) |
| 3a | Secondary Hydraulic Damper |
| 3b | Friction Snubber |
| 3c | Primary Hydraulic Damper |
| 4 | Bearings |
| 5 | Frame |
| 6a | Axles |
| 6b | Gearboxes |
| 7 | Wheels |
| 8a | Brake Linings |
| 8b | Brake Actuator |
| 8c | Brake Disc |
| 9 | Pneumatic System - (Air Reservoir & Leveling Valve) |
| 10 | Alternator (Speed Transducer) |
| 11 | Bolster |
| 12 | Traction Motor |
| A | Components Which Go With Car When Detruck |
| B | Components Which Go With Truck When Detruck |
| C | Wheelset — Axle — Bearing — Gearbox Assembly |
| Y | Yes |
| N | No |
| U | Uncertain |
| - | None |
| Blank | Component Not Contained In Truck |

TABLE 2.5

DESCRIPTION OF MAINTENANCE SUBJECTS

IN CATEGORIZATION TABLES

1. Assembly containing the component such that the assembly and component are removed together for inspection or service.

2. Subassemblies that must have been removed previously for inspection* of this component.

3. Components that must have been removed previously from subassembly for inspection* of this component.

4. Subassemblies that must have been removed previously for major service of this component.

5. Components that must have been removed previously from subassembly for major service of this component.

6. Typical defect mode: B = Broken, W = Wear, F = Fatigue
C = Creep or Bent, L = Leak

7. Is the component repairable*?

---

| | | |
|---|---|---|
| *Inspection | - | The decision regarding whether work on the component is needed. |
| Repairable | - | Defective component which can be maintained, i.e. by adding fluid, replacing subcomponents (O rings, brushes, bushings, etc.), straightening, shimming, cleaning, welding, remachining. |
| Nonrepairable | - | Defective component which no design provision for maintenance has been made, i.e. wear out limits reached (side bearings, snubbers, brake linings, etc.) sealed units (automotive type shock absorbers). |

## TABLE 2.6

## MAINTENANCE CATEGORIZATION TABLE

Truck Type: LRC Passenger Bogie

Component

| Maintenance Subject | 1 | 2 | 3a | 3b | 3c | 4 | 5 | 6a | 6b | 7 | 8a | 8b | 8c | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | B,C | B | - | | - | B,C | B | B,C | | B,C | - | - | B,C | B | | B | |
| 2 | - | - | - | | - | - | - | - | | - | - | - | - | - | | - | |
| 3 | - | - | - | | - | - | - | - | | - | - | - | - | - | | - | |
| 4 | B,C | B | - | | - | B,C | B | B,C | | B,C | - | - | B,C | B | | B | |
| 5 | 5,11, 1,3 | 11,2 | 3a | | 3c | 11,5,1, 3c,7, 4 | 5,11 | 5,11, 7,1,3c, 6a,8c | | 7 | 8a | 8b | 5,1, 3c, 7, 4,8c | 9 | | 5,11 | |
| 6 | W,C | W,L | L,W | | L,W | All | F,C | F,C | | W,F,B | W | W,B, C,L | W,F | L,F | | F,C | |
| 7 | N | Y | Y | | Y | Y | Y | N | | Y | N | Y | Y | Y | | N | |
| | U | | | | | U | | | | U | | U | U | | | U | |

## TABLE 2.7

## MAINTENANCE CATEGORIZATION TABLE

Truck Type: LRC Locomotive

Component

| Maintenance Subject | 1 | 2 | 3a | 3b | 3c | 4 | 5 | 6a | 6b | 7 | 8a | 8b | 8c | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | B,C | B | B | | | B | B | B,C | B,C | B,C | - | - | | - | B | | B,C |
| 2 | B,C | - | B | | | - | - | B,C | B,C | - | - | - | | - | B | | B,C |
| 3 | - | - | - | | | - | - | 6b | - | - | - | - | | - | - | | - |
| 4 | B,C | B | B | | | B | B | B,C | B,C | B,C | - | - | | - | B | | B,C |
| 5 | 1,5 | 2 | 2,3a | | | 5,1, 4 | 2,5, 12 | 5,1, 4,7, 6b,6a | 6b | 5,1, 4,7 | 8a | 8b | | 9 | 10 | | 5,6b, 12 |
| 6 | W,C | B,C, F,L | W,L | | | All | F,C | F,C | W,F,C | W,F,B | W | W,B,C | | L,F | W,B,C | | W,B |
| 7 | N | Y | Y | | | Y | Y | N | Y | Y | N | Y | | Y | Y | | Y |
| | U | | | | | U | U | U | U | | | U | | U | U | | |

## TABLE 2.8

## MAINTENANCE CATEGORIZATION TABLE

Truck Type: BT 10

Component

Maintenance Subject

| | 1 | 2 | 3a | 3b | 3c | 4 | 5 | 6a | 6b | 7 | 8a | 8b | 8c | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | B,C | B | - | | - | B,C | B | B,C | | B,C | - | - | B,C | B | | B | |
| 2 | - | - | - | | - | - | - | B,C | | - | - | - | - | B | | B | |
| 3 | - | - | - | | - | - | - | - | | - | - | - | - | - | | - | |
| 4 | B,C | B | - | | - | B,C | B | B,C | | B,C | - | - | B,C | B | | B | |
| 5 | 1,5 3c | 2 | 3a | | 3c | 5,1, 3c,4 | 1,3c, 2,5 | 1,3c, 5,4,7, 6a | | 1,3c, 5,4,7 | 8a | 8b | 8c | 9 | | 2,3a, 11 | |
| 6 | F,C,W | W,L | W,L | | W,L | All | F,C | F,C | | W,F,B | W | W,B, C,L | W,F | L,F | | F,C | |
| 7 | Y | Y | Y | | Y | Y | Y | N | | Y | N | Y | Y | Y | | N | |
| | | U | U | | | | | | | U | | U | U | | | | |

## TABLE 2.9

## MAINTENANCE CATEGORIZATION TABLE

Truck Type: Y 28

Component

| Maintenance Subject | 1 | 2 | 3a | 3b | 3c | 4 | 5 | 6a | 6b | 7 | 8a | 8b | 8c | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | B,C | B | - | | | B,C | B | B,C | | B,C | - | - | | B | | B | |
| 2 | - | - | - | | | - | - | - | | - | - | - | | - | | - | |
| 3 | - | - | - | | | - | - | - | | - | - | - | | - | | - | |
| 4 | B,C | B | - | | | B,C | B | B,C | | B,C | - | - | | B | | B | |
| 5 | 1,5 | 11,2 | 3a | | | 1,5, 4 | 2,5 | 1,5, 4,7, 6a | | 1,5 4,7 | 8a | 8b | | 9 | | 2,11 | |
| 6 | B,C, F | B,C, F | L,W | | | All | F,C | C,F | | W,F, B | W | W,B, C,L | | L,F | | F,C | |
| 7 | Y | Y | Y | | | Y | Y | N | | Y | N | Y | | Y | | N | |
| | | | U | | | | | | | | | | | | | | |

## TABLE 2.10

## MAINTENANCE CATEGORIZATION TABLE

Truck Type: Y 32

Component

| Maintenance Subject | 1 | 2 | 3a | 3b | 3c | 4 | 5 | 6a | 6b | 7 | 8a | 8b | 8c | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | B,C | B | - | | - | B,C | B | B,C | | B,C | - | B | B,C | B | | A | |
| 2 | - | - | - | | - | - | - | B,C | | - | - | B | - | - | | - | |
| 3 | - | - | - | | - | - | - | - | | - | - | - | - | - | | - | |
| 4 | B,C | B | B | | B | B,C | B | B,C | | B,C | - | B | B,C | B | | B | |
| 5 | 1a,5a 3c | 2a 11a | 3a | | 3c | 1a,3c 5a,4a | 1a,3c, 2a,3a, 11a,5a | 1a,3c, 4a,7a, 8c | | 1a,3c, 4a,7a | 8a | 8b | 1a,3c, 4a,7a, 8c | 9a | | 2a,3a, 11a | |
| 6 | B,C, F | B,C, F | L,W | | L,W | All | F,C | C,F | | W,F B | W | W,B, C,L | W,F | L,F | | F,C | |
| 7 | Y | Y | Y | | Y | Y | Y | N | | Y | N | Y | N | Y | | N | |
| | | | | | | | | | | | | | | | | | |

## TABLE 2.11

## MAINTENANCE CATEGORIZATION TABLE

Truck Type: Y 223

Component

| Maintenance Subject | 1 | 2 | 3a | 3b | 3c | 4 | 5 | 6a | 6b | 7 | 8a | 8b | 8c | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | B,C | B | - | | - | B,C | B | B,C | B,C | B,C | - | - | | B | B | A | B |
| 2 | - | - | - | | - | - | - | - | B,C | - | - | - | | - | B | - | - |
| 3 | - | - | - | | - | - | - | - | - | - | - | - | | - | - | - | - |
| 4 | B,C | B | - | | - | B,C | B | B,C | B,C | B,C | - | - | | B | B | B | B |
| 5 | 1,5, 3c | 2,5, 11 | 3a | | 3c | 1,3c, 5,4 | 1,3c, 2,3a, 5,12 | 1,3c, 4,7, 6b,6a | 6b | 1,3c, 4,7 | 8a | 8b | | 9 | 10 | 11 | 12 |
| 6 | F,C,W | B,C,F | W,L | | W,L | All | F,C | F,C | W,F,L | W,F,B | W | W,B, C,L | | L,F | W,B | F | W,B |
| 7 | Y | Y | Y | | Y | Y | Y | Y | Y | Y | N | Y | | Y | Y | Y | Y |
| | | | | | | U | U | | U | U | | U | | U | U | | U |

## TABLE 2.12

## MAINTENANCE CATEGORIZATION TABLE

Truck Type: Y 224

Component

Maintenance Subject

| | 1 | 2 | 3a | 3b | 3c | 4 | 5 | 6a | 6b | 7 | 8a | 8b | 8c | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | B,C | B | - | | - | B,C | B | B,C | | B,C | - | - | B,C | B | | A | |
| 2 | - | - | - | | - | - | - | B,C | | - | - | - | B,C | - | | - | |
| 3 | - | - | - | | - | - | - | - | | - | - | - | - | - | | - | |
| 4 | B,C | B | - | | - | B,C | B | B,C | | B,C | - | - | B,C | B | | B | |
| 5 | 1,5, 3c | 2,5, 11 | 3a | | 3c | 1a,3c, 5,4 | 1,3c, 2,3a 5 | 1,3c, 4,7, 6a | | 1,3c, 4,7 | 8a | 8b | 8c | 9 | | 2,3a, 11 | |
| 6 | F,C, W | B,C, F | W,L | | W,L | All | F,C | F,C | | W,F,B | W | W,B, C,L | W,F | L,F | | F,C | |
| 7 | Y | Y | Y | | Y | Y | Y | N | | Y | N | Y | Y | Y | | N | |
| | | U | | | | U | U | | | U | | U | U | U | | | |

TABLE 2.13

MAINTENANCE CATEGORIZATION TABLE

Truck Type: Y 225

Component

| Maintenance Subject | 1 | 2 | 3a | 3b | 3c | 4 | 5 | 6a | 6b | 7 | 8a | 8b | 8c | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | B,C | B | - | | - | B,C | B | B,C | B | B,C | - | - | | - | B | | B |
| 2 | - | B | - | | - | - | - | B,C | - | - | - | - | | - | B | | - |
| 3 | - | - | - | | - | - | - | - | - | - | - | - | | - | - | | - |
| 4 | B,C | B | - | | - | B,C | B | B,C | B | B,C | - | - | | - | B | | B |
| 5 | 1,5, 3c | 5,2 | 3a | | 3c | 1,3c, 5,4 | 1,3c, 2,5, 12 | 1,3c, 4,5,7, 6a | 6b | 1,5, 3c,4, 7 | 8a | 8b | | 9 | 10 | | 12 |
| 6 | C,B | F,B, L,W | W,L | | W,L | All | F,C | F,C | W,F,L | W,F,B | W | W,B, C,L | | L,C,F | W,B,C | | W,B, F |
| 7 | Y | Y | Y | | Y | Y | Y | N | Y | Y | N | Y | | Y | Y | | Y |
| | | | | | | U | | U | U | U | U | U | | U | U | | |

## TABLE 2.14

## MAINTENANCE CATEGORIZATION TABLE

Truck Type: Y 226

Component

| Maintenance Subject | 1 | 2 | 3a | 3b | 3c | 4 | 5 | 6a | 6b | 7 | 8a | 8b | 8c | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | B,C | B | - | | - | B,C | B | B,C | B,C | B,C | - | - | | - | | | |
| 2 | - | - | - | | - | - | - | B,C | - | - | - | - | | - | | | |
| 3 | - | - | - | | - | - | - | - | - | - | - | - | | - | | | |
| 4 | B,C | B | - | | - | B,C | B | B,C | B,C | B,C | - | - | | - | - | | |
| 5 | 1,3c 5 | 2,5 | 3a | | 3c | 3c,1, 4 | 2,3a, 1,3c, 5 | 1,3c, 4,7, 6b,6a | 6b | 1,3c, 4,7 | 8a | 8b | | 9 | | | |
| 6 | W,C | F,B,W | W,L | | W,L | All | F,C | F,C | W,F,C | W,F,B | W | W,B, C,L | | L,C,F | | | |
| 7 | Y | Y | Y | | Y | Y | Y | N | Y | Y | N | Y | | Y | | | |
| | | | | | | U | U | | U | U | | U | | U | | | |

## TABLE 2.15

## MAINTENANCE CATEGORIZATION TABLE

Truck Type: ET 403

Component

| Maintenance Subject | 1 | 2 | 3a | 3b | 3c | 4 | 5 | 6a | 6b | 7 | 8a | 8b | 8c | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | B,C | B | - | | - | B,C | B | B,C | B,C | B,C | - | B | B,C | B | B | | B |
| 2 | - | - | - | | - | - | - | - | B,C | - | - | - | - | - | B | | - |
| 3 | - | - | - | | - | - | - | - | - | - | - | - | - | - | - | | - |
| 4 | B,C | B | - | | B | B,C | B | B,C | B,C | B,C | - | B | B,C | B | B | | B |
| 5 | 1,5 3c | 2 | 3a | | 3c | 1,3c, 5,4 | 2,3a, 5,1, 3c | 1,3c, 5,4,7, 6a | 1,3a, 5,4,7, 6a,6b | 1,3c, 5,4,7, 6a | 8a | 8b | 8c | 9 | 10 | | 12 |
| 6 | B,C,F | L,W | W,L | | W,L | All | F,C | F,C | W,F,L | W,F,B | W | W,B, C,L | W,F | L,F | W,B | | W,B |
| 7 | Y | Y | Y | | Y | Y | Y | N | Y | Y | N | Y | Y | Y | Y | | Y |
| | | | | | | | | | U | | | U | U | U | U | | U |

TABLE 2.16

MAINTENANCE CATEGORIZATION TABLE

Truck Type: Minden Deutz

Component

| Maintenance Subject | 1 | 2 | 3a | 3b | 3c | 4 | 5 | 6a | 6b | 7 | 8a | 8b | 8c | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | B,C | B | - | | - | B,C | B | B,C | | B,C | - | B | B,C | B | | B | |
| 2 | - | - | - | | - | - | - | - | | - | - | B | - | - | | - | |
| 3 | - | - | - | | - | - | - | - | | - | - | - | - | - | | - | |
| 4 | B,C | B | B | | B | B,C | B | B,C | | B,C | - | B | B,C | B | | B | |
| 5 | 1,5, 3c | 2, 11 | 3a | | 3c | 1,3c, 5,4 | 1,3c, 5 | 1,3c, 5,4,8c, 7,6a | | 1,3c,5, 4,7 | 8a | 8b | 1,3c, 4,7, 8c | 9 | | 2,3a, 11 | |
| 6 | B,C,F | B,C,F | W,L | | W,L | All | F,C | C,F | | W,F,B | W | W,B, C,L | W,F | L,F | | F,C | |
| 7 | Y | Y | Y | | Y | Y | Y | N | | Y | N | Y | N | Y | | N | |
| | | U | | | | | U | | | U | | | U | | | U | |

## TABLE 2.17

## MAINTENANCE CATEGORIZATION TABLE

Truck Type: FIAT Eurofa

Component

| Maintenance Subject | 1 | 2 | 3a | 3b | 3c | 4 | 5 | 6a | 6b | 7 | 8a | 8b | 8c | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | B,C | B | - | | - | B,C | B | B,C | | B,C | - | B | B,C | B | | A | |
| 2 | - | - | - | | - | - | - | B,C | | - | - | B | - | - | | - | |
| 3 | - | - | - | | - | - | - | - | | - | - | - | - | - | | - | |
| 4 | B,C | B | B | | B | B,C | B | B,C | | B,C | - | B | B,C | B | | B | |
| 5 | 1,5, 3c | 2, 11 | 3a | | 3c | 1,3c, 5,4 | 1,3c, 2,3a, 11,5 | 1,3c, 4,7, 8c | | 1,3c, 4,7 | 8a | 8b | 1,3c, 4,7, 8c | 9 | | 2,3a, 11 | |
| 6 | B,C,F | B,C,F | L,W | | L,W | All | F,C | C,F | | W,F, B | W | W,B, C,L | W,F | L,F | | F,C | |
| 7 | Y | Y | Y | | Y | Y | Y | N | | Y | N | Y | N | Y | | N | |
| | | | | | | | | | | | | | | | | | |

## TABLE 2.18

## MAINTENANCE CATEGORIZATION TABLE

Truck Type: Z1040

Component

| Maintenance Subject | 1 | 2 | 3a | 3b | 3c | 4 | 5 | 6a | 6b | 7 | 8a | 8b | 8c | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | B,C | B | - | | B,C | B,C | B | B,C | B,C | B,C | - | - | | B | B | B | B |
| 2 | - | - | - | | - | - | - | - | - | - | - | - | | - | B | - | - |
| 3 | - | - | - | | - | - | - | - | - | - | - | - | | - | - | - | - |
| 4 | B,C | B | - | | B,C | B,C | B | B,C | B,C | B,C | - | - | | B | B | B | B |
| 5 | 1,5 | 11,2 | 3a | | 1,3a | 1,5, 4 | 1,5 | 1,5 4,6b, 6a | 6b | 1,5 4,7 | 8a | 8b | | 9 | 10 | 2,3a 5,11 | 12 |
| 6 | B,C, F,L | B,C,F | W,L | | W,L | All | F,C | C,F | W,F,L | W,F,B | W | W,B, C,L | | L,F | W,B | F,C | W,B |
| 7 | Y | Y | Y | | Y | Y | Y | N | Y | Y | N | Y | | Y | Y | N | Y |
| | | | | | | U | | | U | | | U | | U | U | | U |

## TABLE 2.19

## MAINTENANCE CATEGORIZATION TABLE

Truck Type: DT 200

Component

| Maintenance Subject | 1 | 2 | 3a | 3b | 3c | 4 | 5 | 6a | 6b | 7 | 8a | 8b | 8c | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | B,C | A | - | | - | B,C | B | B,C | B,C | B,C | - | - | B,C | B | B | A | B |
| 2 | - | - | - | | - | - | B | - | - | - | - | - | - | B | B | - | - |
| 3 | - | - | - | | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 4 | B,C | B | - | | - | B,C | B | B,C | B,C | B,C | - | - | B,C | B | B | B | B |
| 5 | 1,3c, 5 | 2,5 | 3a | | 3c | 1,3c, 5,4 | 1,3c, 2,3a 5 | 5,1,3c, 4,7, 6a | 6b | - | 8a | 8b | 8c | 9 | 10 | 2,3a, 11 | 12 |
| 6 | F,C,W | W,L | W,L | | W,L | All | F,C | F,C | W,F,C | W,F,B | W | W,B, C,L | W,F | L,F | W,B,C | F,C | W,B |
| 7 | Y | Y | Y | | Y | Y | Y | N | Y | Y | N | Y | Y | Y | Y | N | Y |
| | | U | | | | | U | | U | U | | U | U | U | U | | U |

## TABLE 2.20

## MAINTENANCE CATEGORIZATION TABLE

Truck Type: P III

Component

| Maintenance Subject | 1 | 2 | 3a | 3b | 3c | 4 | 5 | 6a | 6b | 7 | 8a | 8b | 8c | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | B,C | A | - | | | B,C | B | B,C | | B,C | - | - | - | A | | A | |
| 2 | - | - | - | | | - | - | B,C | | - | - | - | - | - | | - | |
| 3 | - | - | - | | | - | - | - | | - | - | - | - | - | | - | |
| 4 | B,C | B | - | | | B,C | B | B,C | | B,C | - | - | - | B | | B | |
| 5 | 1,5 | 2,11 | 3 | | | 1,5 7,4 | 11,5 | 7,5 1,4 8c,6a | | 7 | 8a | 8b | 8c | 9,11 2 | | 2,11 | |
| 6 | W,C | F,B, L,W | W,L | | | All | F,C | F,C | | W,F | W | W,B, C,L | F,W | L,F, C | | F,C | |
| 7 | N | Y | Y | | | Y | Y | Y | | Y | N | Y | N | Y | | N | |
| | | | | | | | | | | | | | | | | | |

## TABLE 2.21

## MAINTENANCE CATEGORIZATION TABLE

Truck Type: Metroliner

Component

| Maintenance Subject | 1 | 2 | 3a | 3b | 3c | 4 | 5 | 6a | 6b | 7 | 8a | 8b | 8c | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | B | A | - | B | | B,C | B | B,C | B,C | B,C | - | B | | - | B | A | B |
| 2 | - | - | - | - | | - | B | B,C | B,C | - | - | B | | B | B | - | - |
| 3 | - | - | - | - | | - | - | - | - | - | - | - | | - | - | - | - |
| 4 | B,C | B | - | B,C | | B,C | B,C | B,C | B,C | B,C | - | B | | B | B | B | B |
| 5 | 1,5 | 2 | 3a | 3b | | 4 | - | 4,6a 6b,7 | 4,6a 6b,7 | 4,7 | 8a | 8b | | 9 | 10 | 11 | 12 |
| 6 | F,C, B | F,B, W | L,W | W | | All | F,C | C | W,F, L | W,F, B | W | W,B, C,L | | L,F | W,B | F | W,B |
| 7 | Y | Y | Y | N | | Y | Y | N | Y | Y | N | Y | | Y | Y | Y | Y |
| | | | | | | | | | | | | | | | | | |

## TABLE 2.22

## MAINTENANCE CATEGORIZATION TABLE

Truck Type: ER 200

| Maintenance Subject | Component 1 | 2 | 3a | 3b | 3c | 4 | 5 | 6a | 6b | 7 | 8a | 8b | 8c | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | B,C | A | - | | - | B,C | B | B,C | B,C | B,C | - | - | B,C | B | B | A | B |
| 2 | - | - | - | | - | - | B | B,C | - | - | - | - | - | B | B | - | - |
| 3 | - | - | - | | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 4 | B,C | B | - | | - | B,C | B | B,C | B,C | B,C | - | - | B,C | B | B | B | B |
| 5 | 1,3c, 5 | 5,2 | 3a | | 3c | 1,3c, 5,4 | 1,3c, 2,3a, 5 | 1,3c, 5,4, 7,6a | 6b | 1,3c, 4,5, 7 | 8a | 8b | 8c | 9 | 10 | 2,3a, 11 | 12 |
| 6 | F,C,W | W,L | W,L | | W,L | All | F,C | F,C | W,F,C | W,F,B | W | W,B, C,L | W,F | L,F | W,B,C | F,C | W,B |
| 7 | Y | Y | Y | | Y | Y | Y | N | Y | Y | N | Y | Y | Y | Y | N | Y |
| | | | | | | U | | | U | U | | U | | | U | | U |

The operational framework for the maintenance of the Metroliner by Amtrak is shown in Figure 2.4. This figure, which also is appropriate for Amtrak in general, shows the manner in which a truck is processed for maintenance.

The figure indicates that the car in service is given an inspection in the car shop. The results of that inspection can be routine service or some amount of repairs. The repair can be in-place or can require removal of the primary truck (truck frame and associated components). If removal is required, this can be for secondary suspension repair or for primary truck repair. In the latter case, the truck is further inspected and, if necessary, disassembled to a greater extent. Upon completion of all appropriate repair work, successive reassembly restores the truck and car to service.

The specific actions taken within the several boxes of Figure 2.4 depend on the individual characteristics and requirements of a particular truck. It is at this point that the maintenance requirements of Section 2.2 combine with the operational framework. The result is the schematic diagram which describes Amtrak's maintenance of that truck. These diagrams for the Metroliner truck and for the Amcoach truck are given in the next section (Section 3).

## 2.4 Review of the Survey and Analysis of Truck Technology and Usage

The large number of sources used for the literature search and the participation of the Budd Company in the literature search suggest that a rather complete list of current high speed trucks has been produced.

The characterization of these trucks in terms of generic design concepts is complete for such familiar trucks as the Metroliner, Turbotrain, Pioneer III, E-60, etc. The characterization is not complete for many of the other trucks, particularly those manufactured or used overseas.

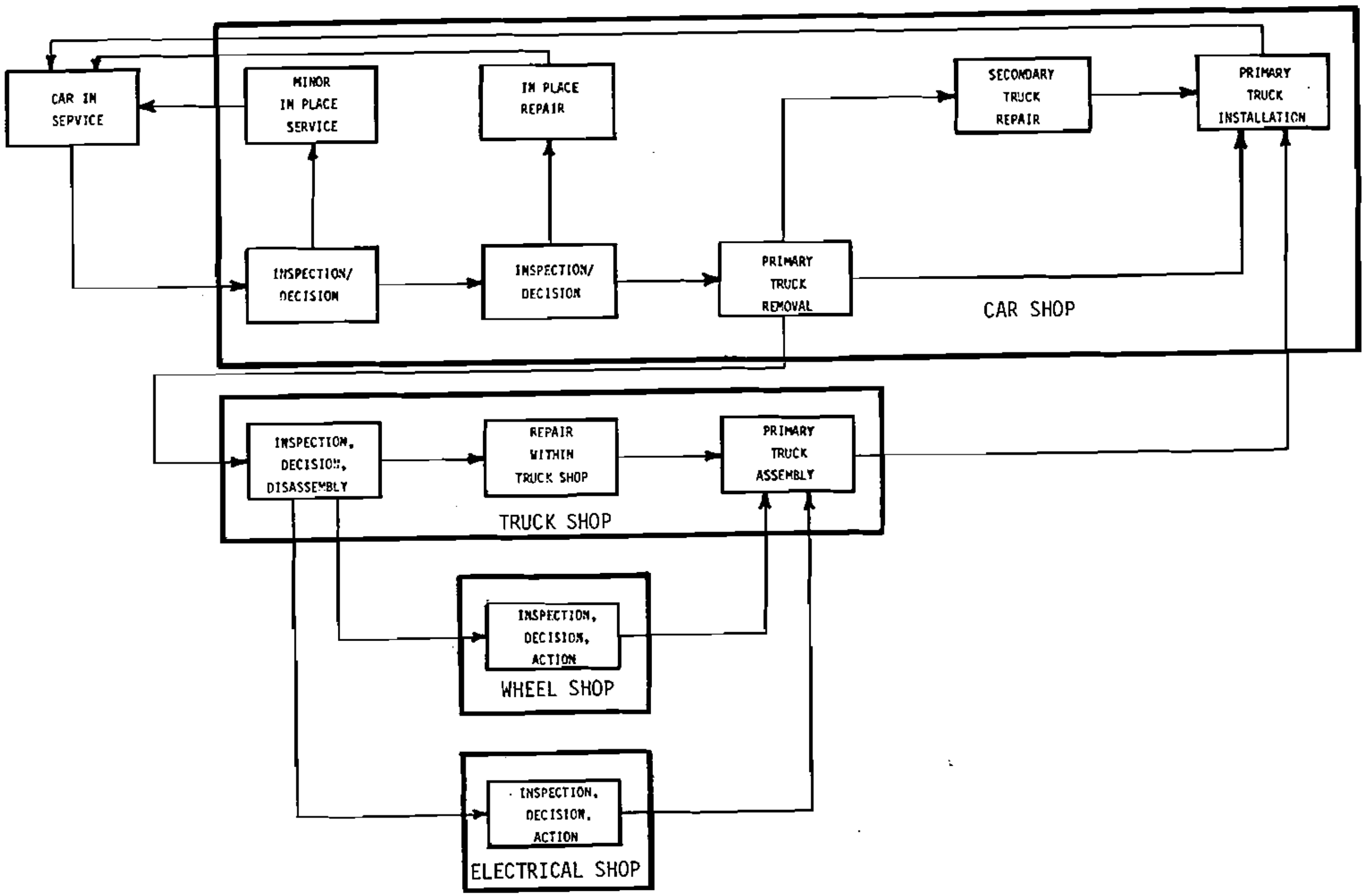



FIGURE 2.4 METROLINER OPERATIONAL FRAMEWORK

There exist little published maintenance data for any one truck. The majority of such data have to be obtained from the user and manufacturer of the truck.

The procedure for the maintenance categorization of high speed trucks has been developed and applied. This procedure is directly suited to the development of schematic diagrams for the simulation cost model. The application of the procedure to each of the more familiar trucks is complete.

The nature of the operational framework in relation to the simulation cost modelling technique has been defined. An operational framework for Amtrak has been developed.

## 3. SCM MAINTAINABILITY MODEL

The SCM technique is, essentially, a representation of the maintenance actions which affect the truck. This representation employs a schematic diagram which describes how a particular railroad maintains a particular type of truck. A computer program is used to implement the diagram and the associated data. The data requirements for the computer program are defined in large part by the schematic diagram.

The SCM technique calculates the cost per unit time (typically, a year) required by the system under consideration (e.g., Amtrak) to operate the truck under consideration. Operation includes both maintenance costs and costs to acquire parts. The calculation involves three parts: a schematic diagram, the computer program, and data. Each of these parts is described briefly below (technical descriptions of portions of the technique are given in more detail in Subsection 3.3).

### 3.1 Schematic Diagram

The schematic diagram identifies the truck-related parts of the system, the interactions which involve the truck and its components, and the decisions which take place concerning the truck. To describe the schematic, a very simple diagram can be used. This diagram is illustrated in Figure 3.1. This figure is a simplified schematic diagram for a portion of the railroad freight car roller bearing system. The portion shown is for the costs attributable to roller bearings because of hot box setouts.

Several segments of the system are shown in the diagram. "In use" is productive operation of the bearings. "Field" includes actions taken regarding bearings but associated with their productive use. "Yard" refers to the classification yard. "Wheel Shop" is where demounting of the bear- from the axle occurs. "Bearing Shop" is where bearing maintenance occurs.

The figure indicates that bearings move from In Use along path 39 (uncircled number). This path contains those bearings involved in hot box indications

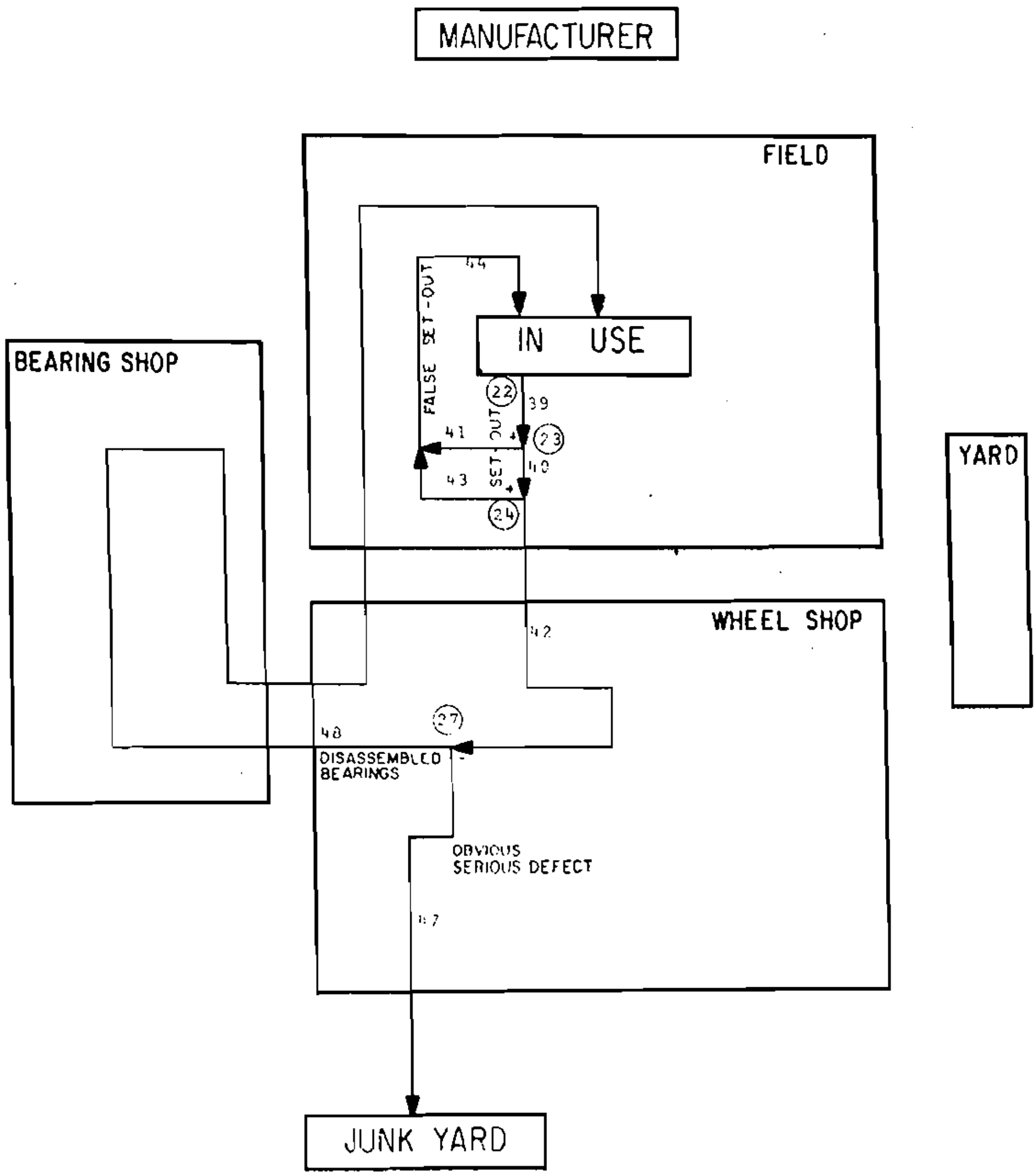



FIGURE 3.1 ROLLER BEARING SYSTEM COST MODEL FOR SET-OUTS

to the train crew. Path 40 contains those bearings whose hot box indications have been verified by the train crew. Falsely setout bearings return to In Use via path 41. The decision made by the train crew occurs at node (23). A similar decision, made by the Mechanical Department, occurs at node (24). Hot bearings so verified at node (24) move along path 42 to the wheel shop. At the wheel shop, disassembly of the bearing from its axle occurs as does a joint inspection. Some bearings are discarded at node (27) along path 47. The remaining bearings are disassembled, sent to the bearing shop for service, and eventually remounted on an axle and returned to In Use.

It is apparent from the diagram that the schematic merely identifies and illustrates how the truck (its roller bearing in this example) is used. The movements within various parts of the diagram are along the paths. Each path is characterized in terms of flow rate (e.g., bearings per year), age, and quality. The quality, in turn, is defined as the proportion of those components in the path which are defective by AAR or by Amtrak rules. Each path can have an associated cost.

Nodes identify points at which path flows divide (branch points) or join (summation points). At each branch point, a decision affecting the truck or its component occurs. This decision can be the proportion, C, of arriving units which moves along one of the two departing paths. The decision can also be for the proportion, D, of arriving defective components correctly called defective and for the proportion, E, of arriving good components erroneously called defective (see Subsection 3.3 for a complete discussion of these points).* At summation points, no decision affecting the component occurs.

---

*The symbols —, +, ?, and S are not formally part of the SCM technique. They are intended as an aid for this example and are defined as follows:

- \+ Denotes flow of components whose condition is acceptable.
- — Denotes flow of components whose condition cannot be made acceptable.
- ? Denotes flow of components whose condition is not acceptable. This flow contains "—" components as well as those which, with suitable rework or repair, can be made acceptable.
- S Denotes flow of components which, with suitable rework or repair, can be made acceptable.

The example used for the discussion above contained only one component (the freight car railroad roller bearing). The present program is concerned with the entire high speed passenger train truck. The essential difference is that, in the high speed truck case, a large number of components and their interactions must be considered simultaneously. This requires a more complex schematic diagram (and associated computer program and data). A part of such a diagram is shown in Figures 3.2 - 3.4. The schematic diagram is for the Metroliner truck.

As with the freight car roller bearing example, the schematic of Figures 3.2 - 3.4 considers individual portions of the maintenance system. These portions are "In Service", "Car Shop" and "Truck Shop". Each portion is shown on a separate page to allow preparation of the schematic diagram in a "modularized" fashion.

The notation for the truck schematic is similar to that used above for the roller bearing example. The paths, uncircled numbers, indicate movements of truck components. In general, all of the components can be associated with a particular path (if there are twelve truck components, each path can represent, simultaneously, twelve flows). Each of the twelve flows consist of three quantities - the number per year for the particular component, the representative age of the component, and the quality (proportion defective) for the component flow.

The points at which the paths separate or join are identified by circled numbers. Joining points are summation points. Separation points are branch or decision points - at these points decisions and appropriate data are required. These data can consist, for each component at each node, of

a) a value for the parameter C

b) values for the parameters D and E

c) a value for the parameter G (described below)

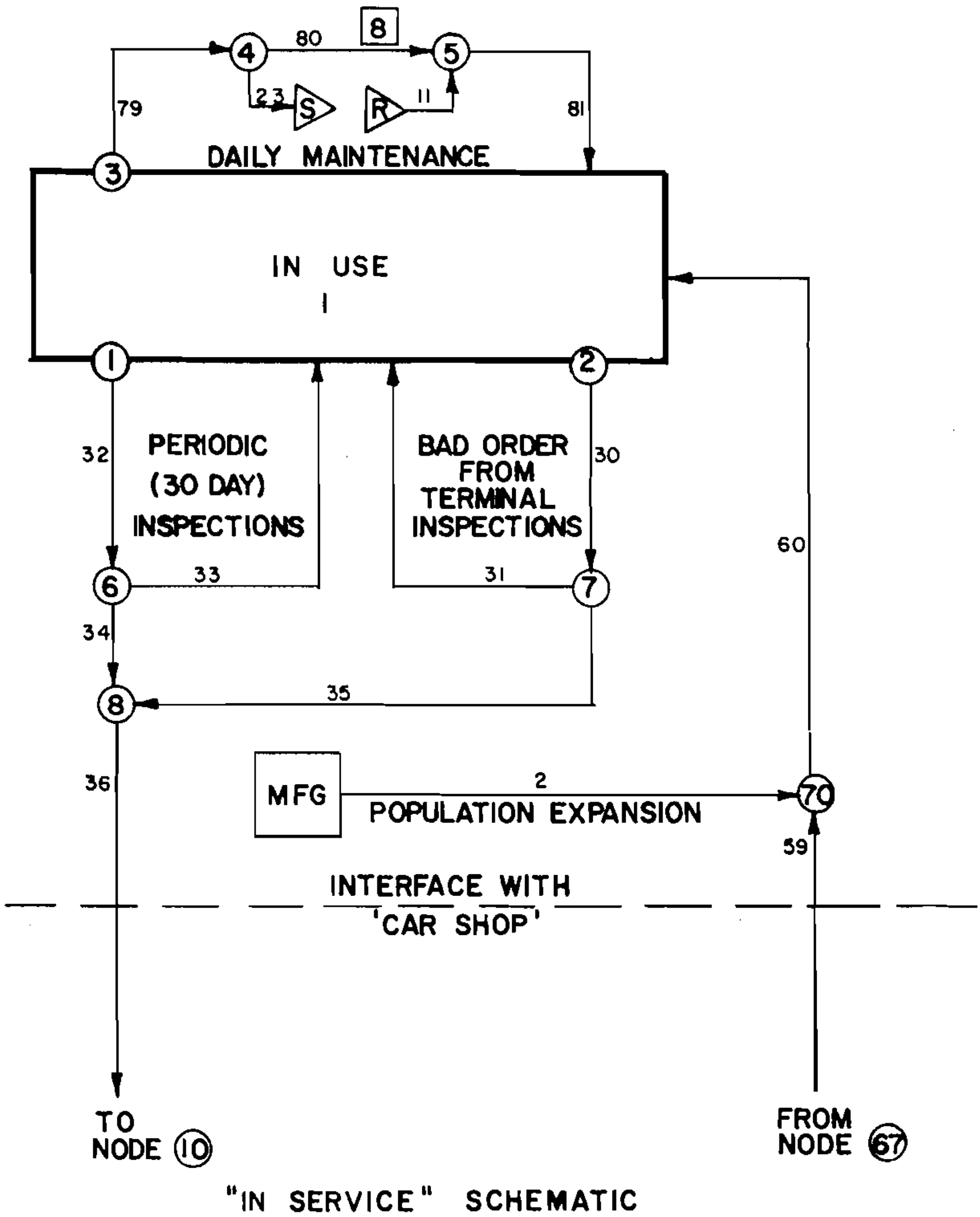
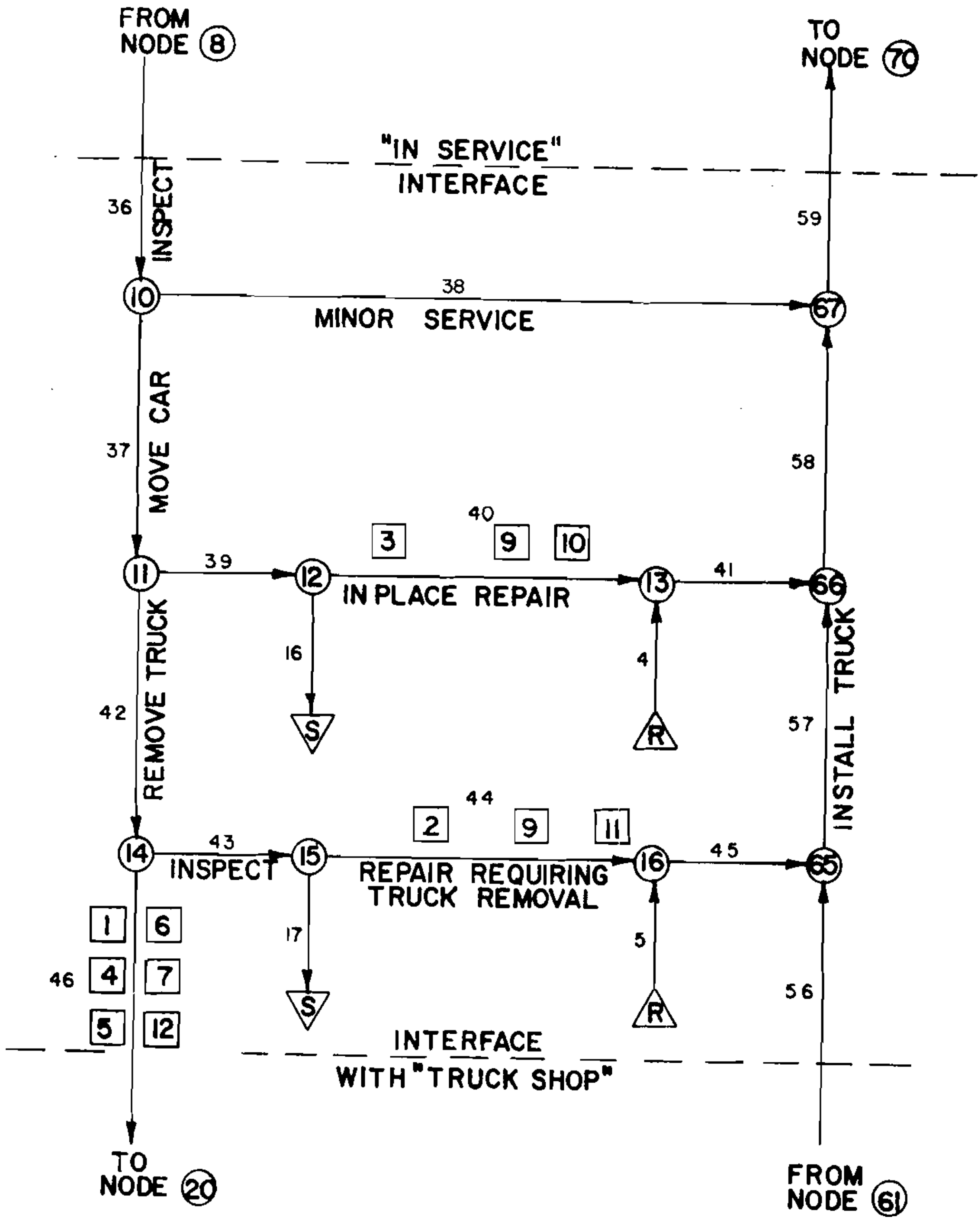
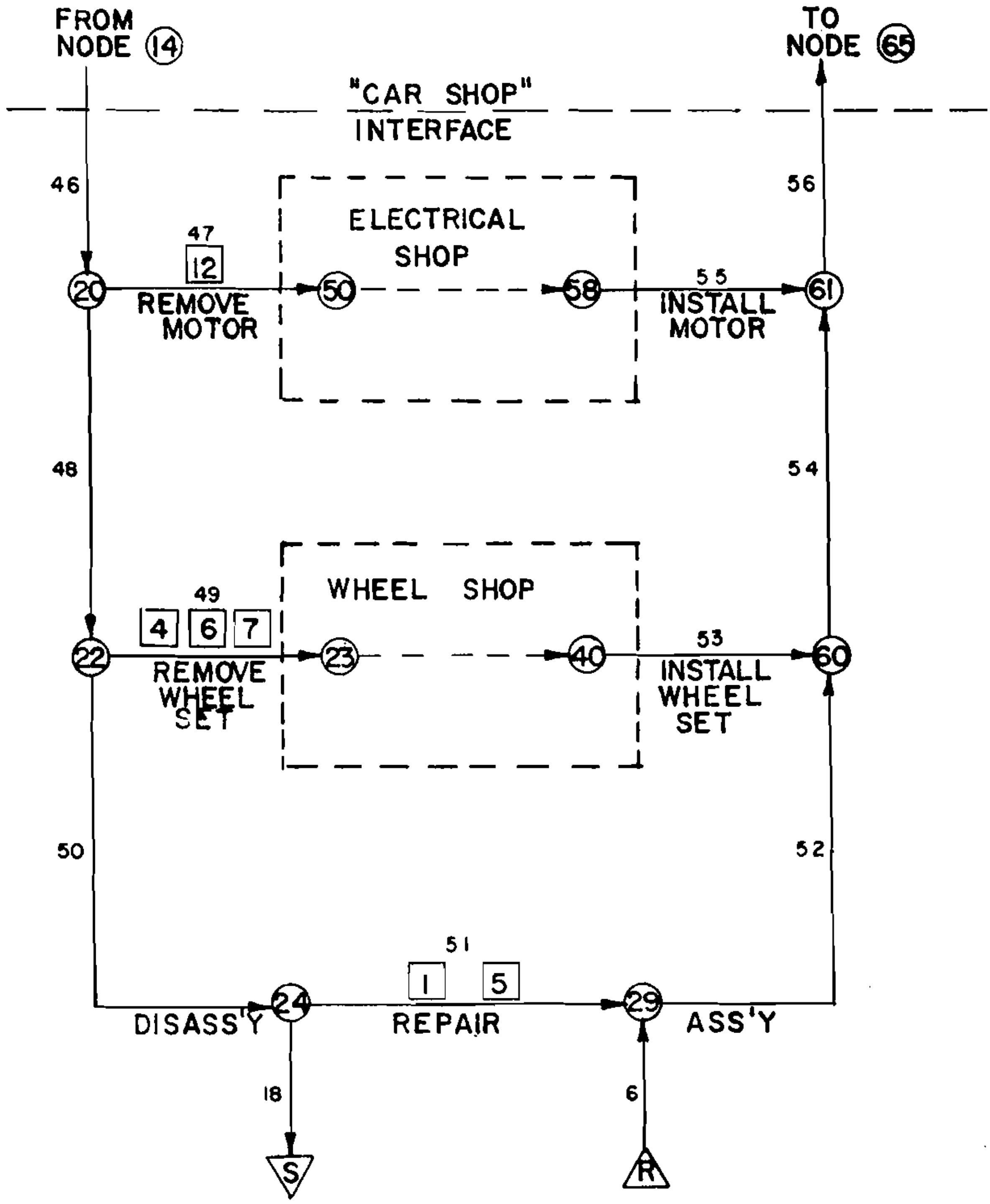



FIGURE 3.2 METROLINER SCHEMATIC




"CAR SHOP" SCHEMATIC

FIGURE 3.3 METROLINER SCHEMATIC




"TRUCK SHOP" SCHEMATIC

FIGURE 3.4 METROLINER SCHEMATIC

d) a specification of which components comprise a subassembly which is treated as a unit (described below)

e) any general function (nonlinear, time dependent, etc.) which describes the action concerning the component which occurs at the node.

Typically, data of the form a)-d) are sufficient to describe the actions concerning each component which take place at the branch node. Decision a) is the simplest and specifies that a proportion C of the arriving flow for the component branches to one of the outgoing paths. Decision b) specifies that a proportion D of the arriving good flow for the component and a proportion E of the arriving bad flow for the component branch to one of the outgoing paths. Decision c) specifies that the proportion of the arriving flow for the component which branches to one of the outgoing paths depends on the representative age in the arriving path. Specifically, the majority of the flow switches from one of the paths to the other path when the representative age in the arriving path equals the G value specified.* The data d) specify component interdependencies. For example, if a truck is removed from a car because of, say, a wheel problem, the wheel and the other components of the truck must be removed from the car simultaneously. The data d) preserve the identity of distinguishable subsystems such as the truck or the wheelset.*

In general each path will have a cost or costs associated with it. Typically the cost will be given in terms of the dollars per each component on the path. In certain cases, the cost will be given in terms of the dollars per each defective component on the path.

To illustrate the meaning of the schematic diagram, consider Figure 3.3. This figure shows the maintenance actions that are taken for the Metroliner when it enters the "Car Shop" or maintenance facility. Upon entering the Car Shop (Path 36) the truck is inspected. If no problems requiring maintenance are

*See Subsection 3.3

detected, all truck components move along Path 38 for minor and periodic service. If problems in particular components are encountered, these "problem components" and their associated trucks are moved physically in the shop (repsented by Path 37). At node 11, problem components $\boxed{3}$, $\boxed{8}$, $\boxed{9}$, and $\boxed{10}$ are separated from the rest, i.e., along path 39. (See Table 3.1 for the definitions of which components are associated with the numbers in square boxes.) Their associated good truck components also "move" along path 39. The problem components are repaired on path 40. If necessary, some of the problem components are scrapped (path 16) and replaced (path 4). The other problem components and their associated good components move along path 42. On this path, the truck is removed from the car. Problem components $\boxed{2}$, $\boxed{9}$, and $\boxed{11}$ and their associated good primary trucks are treated on paths 43 - 45. Problem components $\boxed{1}$, $\boxed{4}$, $\boxed{5}$, $\boxed{6}$, $\boxed{7}$, and $\boxed{12}$ and their associated good components comprise the primary truck. These are sent to the "Truck Shop" for further action. Actions similar to those described above take place in the truck shop and, subsequently, in the electrical shop and wheel shop.

## 3.2 Computer Program

The computer program has the task of implementing the schematic diagram and of performing the tasks described previously.

The program, written in the BASIC computer language, has the capability of producing the following outputs:

a) Printout of schematic topology
b) Computation of the base or reference case
c) Sensitivity analysis
d) Prediction of future truck usage and costs

Each of these outputs is described briefly below.

The computer program is completely independent of the particular truck and operating system (e.g. Amtrak) which are being treated. The computer pro-

TABLE 3.1

COMPONENT DESIGNATION

| | |
|---|---|
| $\boxed{1}$ | PRIMARY SPRINGS |
| $\boxed{2}$ | SECONDARY SPRINGS |
| $\boxed{3}$ | DAMPERS |
| $\boxed{4}$ | BEARINGS |
| $\boxed{5}$ | FRAMES |
| $\boxed{6}$ | AXLES/GEAR BOXES |
| $\boxed{7}$ | WHEELS |
| $\boxed{8}$ | BRAKES |
| $\boxed{9}$ | PNEUMATIC SYSTEMS |
| $\boxed{10}$ | ALTERNATORS |
| $\boxed{11}$ | BOLSTERS |
| $\boxed{12}$ | MOTORS |

gram first accepts data which define the number of components in the truck, the number of nodes, the number of paths, etc. The program then accepts data which define the topology of the schematic diagram (the node and path numbering, the manner in which the paths are connected, tec.). The program then "assembles" the schematic diagram numerically during the execution process. In order to assess whether the node and path data have been correctly specified, the user can request a printout of the topology of the schematic diagram. This printout contains, for each node, the information:

1. Node number
2. Branch node number (in terms of a sequential numbering of all branch nodes)
3. The paths associated with the node.
4. The rework (if any) associated with the path(s) from the node and the component(s) being reworked.

If the printout of the topology is found to agree with that necessary for the schematic being treated, the computer program is instructed to compute the base or reference case. This base or reference case is a description of the present annual truck usage and costs. To perform the computation, additional data are needed by the program. These data are the values for the decision parameters for each component at each node, the unit costs* for each component on each path, and the number, representative age, and quality (proportion defective) for each component in the population.

The base case results from a "sweep" through the nodes of the schematic. Starting at node 1, the variables on the path out of node 1 are computed. These variables are the number/year, representative age, and quality for each component on the path. At node 2, a similar computation is made for the variables on the output(s) from node 2. The computation proceeds node by node - if the node under consideration is a branch node, two paths leave from the node and the decision parameters for that node are employed. If the node under consideration is a summation node, the values of the variables on the one leaving path result from the values of the variables on the two input paths. During the sweep through the nodes, the program accounts automatically

*It should be noted that additional data, if available, can be used by the model. For example, nonlinear and/or time varying representations for the path costs, decisions, etc. can be employed directly.

for such events as reworking of components on particular paths and discarding of components on other paths. (Discarded components are compensated automatically with flows of replacement components.)

At the end of the nodal sweep, the paths of the schematic are reviewed to assess the path costs. In this, the unit cost data are employed. For each path, the number of components, number of good components, or number of bad components, together with the unit costs, determine the path cost for each component of the truck. A summation over the components and then over the paths produces the annual operating cost for the base or reference case.

The reference case is generally that used in the production of the sensitivity analysis. The sensitivity analysis is the change in annual system operating cost produced by a change in a decision parameter or in a unit path cost. It has as its primary purpose the identification of decisions and cost elements which most affect the system operating cost. Such an identification can be very helpful in determining which data values should be most accurately estimated.

To produce the sensitivity analysis, the reference case is automatically run repeatedly -- for each run the values of all C, D, E, G, or unit path costs are varied slightly. The results are the change in total operating cost (maintenance and acquisition cost) associated with a 1% change in

- o the number of units branching to one of the outgoing paths at the node (C decision), or

- o the number of defective units branching to one of the outgoing paths at the node (D decision), or

- o the number of good units branching to one of the outgoing paths at the node (E decision), or

- o the number of identifiable subassemblies branching to one of the outgoing paths at the node (K$ decision - See Section 3.3)

- o the age at which the majority of the units switches from one of the outgoing paths to the other outgoing path (G decision), or

- o the unit path cost for each component.

Prediction of future truck usage and costs involves using the computer program in its dynamic simulation mode. In order to run the SCM in this mode, data in addition to those mentioned above are required. These data are, for each component, its Weibull slope, its characteristic life, and the rate at which its population size is planned to change with time.

To perform the simulation, the program performs the following steps:

1. Using known values of the time, decision parameters, and the size, representative age, and quality (proportion defective) for each component's population, the program does calculations as for the reference case. The results of this are the number, age, and quality for each component on each path.

2. For each component and each path, the program computes the associated cost. A summation over all paths gives the annual operating cost.

3. The rates of change of the population size, age, and quality for each component are computed. These rates of change are used to predict the size, age, and quality (the state variables) for each component at the next time of interest.

4. At the next time, steps 1 and 2 are repeated. Since the decision parameters and individual paths costs can vary with time and/or with population size, age, and quality, a new set of flows and costs are computed. Continuation of the process produces a dynamic simulation projection of component usage and cost at future times.

## 3.3 Details of the Branch Node Decisions (Parameters C, D, E, K$, and G)

The characterization of each component on each path in terms of quantity (number per year), representative age, and quality (proportion defective) allows relatively general decisions to occur at each branch point. The decisions can be nonlinear functions of time, of the number of units in the arriving path, of the representative ages in the path, and of the qualities in the path. From the set of possible decisions, four are deemed to be representative of actual events which involve the truck. These are:

1. The decision made for a component (component k) is not dependent on its quality in the arriving stream. Specifically, if $N_k$ units per year arrive at the node, $C_k N_k$ units branch to one of the outgoing paths and $(1-C_k)\cdot N_k$ units branch to the other outgoing path. The $C_k$ value defines the decision and can be obtained either directly or indirectly from available data. In general $C_k$ can be a known function of time.

2. The decision made for a component (component k) is dependent on its quality in the arriving stream. Specifically, a proportion $D_k$ of the arriving defective units are correctly classified as defective and a proportion $E_k$ of the arriving good units are incorrectly identified as defective. If $N_k$ units per year having a quality of $Q_k$ arrive at the node, then the proportion $C_k$ of arriving units which branches to the path intended for the defective units is given by $D_k Q_k + E_k \cdot (1 - Q_k)$. In addition, the quality $Q_{1k}$ on that departing path is $D_k Q_k / (D_k Q_k + E_k \cdot (1 - Q_k))$. The proportion which branches toward the other departing path and the quality on that path are obtained from conservation-of-flow requirements at the branch point. The values of $D_k$ and $E_k$ define the decision and can be obtained either directly or indirectly from available data. In general, $D_k$ and $E_k$ can be known functions of time.

3. The decision made for a component (component k) is dependent on the representative age, $A_k$, of the component in the arriving stream. Specifically, the decision to switch the majority of the flow from one of the outgoing paths to the other outgoing path is made when $A_k$ is equal to $G_k$. If $N_k$ units per year arrive at the node, then the proportion $C_k$ of arriving units which branches to the path intended for defective units is given by $A_k/(2G_k)$. In addition, the representative age $A_{1k}$ on that departing path is $2 \cdot G_k$. The constant $G_k$ defines the decision and can be obtained directly or indirectly from available data. In general, $G_k$ can be a known function of time.

4. The decision made for a component (component k) is affected by the decision made for other components at the branch point. The interelationship arises because these components, identified in the nodal data by the parameter K$, are part of a distinquishable subassembly. For any such component, if $N_k$ units per year having a representative age of $A_k$ and a quality of $Q_k$ arrive at the node, the proportion $C^*$ of each which branches to the path intended for defective units is $C^*=1-\prod_K(1-C_k)$. The product is taken over all K components in the subassembly. The representative age and quality on that departing path are respectively

$$A_{1k} \cdot C_k/C^* + \frac{A_k - C_k A_{1k}}{A_k}(1-C_k/C^*) \qquad \text{and}$$

$$Q_{1k} \cdot C_k/C^* + \frac{Q_k - C_k Q_{1k}}{Q_k}(1-C_k/C^*).$$

The quantity $C_k$ is that of 1 (or the equivalent $C_k$ of 2 or 3) and is evaluated prior to the coupling of the decision for component k with those for the other components in the subassembly.

The expressions in 1 and 2 are easily obtained by considering Figure 3.5. This figure shows an arriving stream having a flow of $N_k$ units per year and a quality of $Q_k$. The flow towards path 1 must be

$$N_{1k} + D_k Q_k N_k + E_k \cdot (1-Q_k) \cdot N_k$$

The proportion which branches towards path 1 is then

$$C_k = \frac{N_{1k}}{N_k} = \frac{D_k Q_k N_k + E_k \cdot (1-Q_k) \cdot N_k}{N_k} = D_k Q_k + E_k \cdot (1-Q_k)$$

The flow of defective components on path 1 is $D_k Q_k N_k$. Consequently the quality on path 1 is

$$Q_{1k} = \frac{D_k Q_k N_k}{N_{1k}} = \frac{D_k Q_k N_k}{D_k Q_k N_k + E_k \cdot (1-Q_k) \cdot N_k}$$

$$= \frac{D_k Q_k}{D_k Q_k + E_k \cdot (1-Q_k)}$$

The expression in 3 above arises from the requirements that the flow be equally split to the two outgoing paths when $A_k = G_k$ and that the flow to the path intended for defective units be zero when $A_k = 0$. These requirements are satisfied by the straight line $C_k = (1/2\ G_k) \cdot A_k$.

The straight line also gives $C_k = 1$ at $A_k = 2 \cdot G_k$. Consequently, if the age on the path intended for defective units is set to $2 \cdot G_k$, the $C_k$ values at the downstream age decision nodes are equal to 1. Consequently, downstream age decisions (e.g. - reworking or discarding) are properly produced by upstream age decisions (e.g. identification of trucks with an overage component).

The first expression in 4 can be obtained by regarding the $C_k$ decisions for the K components in the subassembly to be statements of probability. For

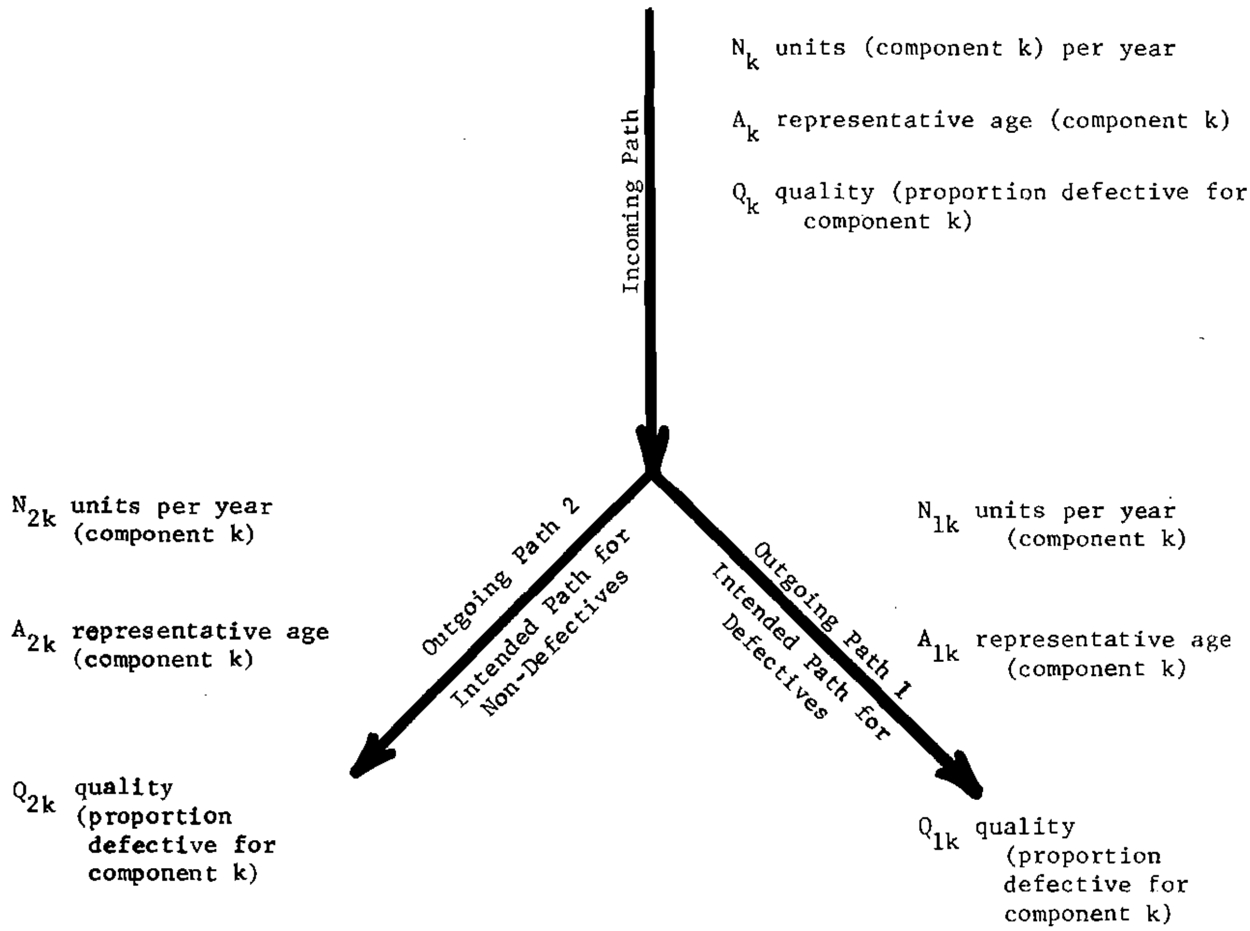



FIGURE 3.5 BRANCH NODE DECISIONS

component k, the probability that a given unit will branch to the path intended for good units is $1-C_k$. For all components in the subassembly, the probability that, treated individually, all units will branch to that path is $\prod_K (1-C_k)$. Because these components are part of the same subassembly, all must be intended for that path if the subassembly is to branch to that path.

As a result, the proportion of arriving subassemblies branching to the path intended for good units is $\prod_K (1-C_k)$ and the proportion of arriving subassemblies branching to the path intended for defective units is $1 - \prod_K (1-C_k)$.

The relationships for age and quality in 4 can be obtained by considering the additional units required to produce complete subassemblies. For component k, the number of units branching to the path intended for defective units is $C_k N_k$ if the component is treated individually. The associated age and quality for the component on the path are $A_{1k}$ and $Q_{1k}$. The increase in the number of units on the path to maintain integral subassemblies is $(C^* - C_k) \cdot N_k$. This increased number has an age and a quality equal to the ones in the outgoing path 2 (see Figure 3.5). Consequently, the age and quality on the departing path intended for defective units are changed from

$$\frac{A_{1k} C_k N_k}{C_k N_k} \quad \text{and} \quad \frac{Q_{1k} C_k N_k}{C_k N_k}$$

to

$$\frac{A_{1k} C_k N_k + A_{2k} (C^* - C_k) N_k}{C_k N_k + (C^* - C_k) N_k} \quad \text{and} \quad \frac{Q_{1k} C_k N_k + Q_{2k} (C^* - C_k) N_k}{C_k N_k + (C^* - C_k) N_k} \tag{1}$$

where $C^* N_k$ is the total number of units on the path. The quantities $A_{2k}$ and $Q_2 k$ are the age and quality on the outgoing path 2 before coupling of the decision for component k with those for other components in the subassembly. The quantities $A_{2k}$ and $Q_{2k}$ can be eliminated from the above expressions as follows. The number of units on the outoing path 2 for component k, treated individually, is $N_k(1-C_k)$. The representative age and quality of these units are determined by the ages and qualities on the input path and on the outgoing path 1 (see Figure 3.5). These are

$$A_{2k} = \frac{A_k N_k - A_{1k} N_{1k}}{N_{2k}}$$

$$Q_{2k} = \frac{Q_k N_k - Q_{1k} N_{1k}}{N_{2k}}$$

or, after using $N_{1k} = C_k N_k$ and $N_{2k} = N_k(1-C_k)$

$$A_{2k} = \frac{A_k N_k - A_{1k} C_k N_k}{N_k(1-C_k)}$$

$$Q_{2k} = \frac{Q_k N_k - Q_{1k} C_k N_k}{N_k(1-C_k)}$$

Upon substitution of these equations into expressions (1) above, the relationships in 4 result.

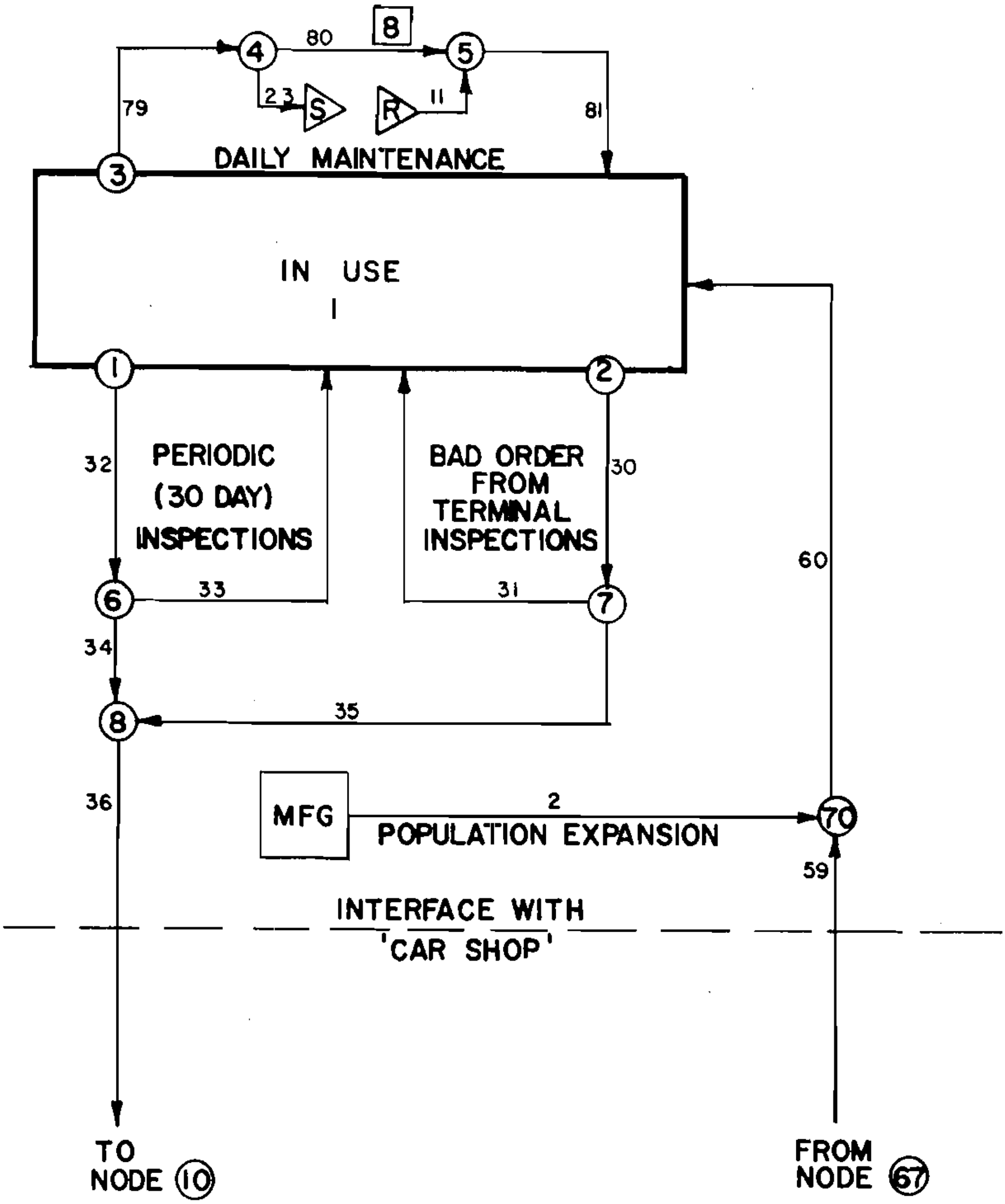
### 3.4 Schematic Diagrams

The simulation cost model is being applied in the present work to two trucks. These trucks are the Metroliner truck and the Amcoach truck. A portion of the schematic diagram for the Metroliner truck was presented in Section 3.1. The complete schematic diagram for this truck is given in Figures 3.6 to 3.10. Table 3.1, which identifies the component numbers in the schematic, is repeated for convenience as Table 3.2.

The schematic diagram for the Amcoach truck is given as Figures 3.11 and 3.12. The table which identifies the component numbers for the Amcoach schematic is given as Table 3.3.

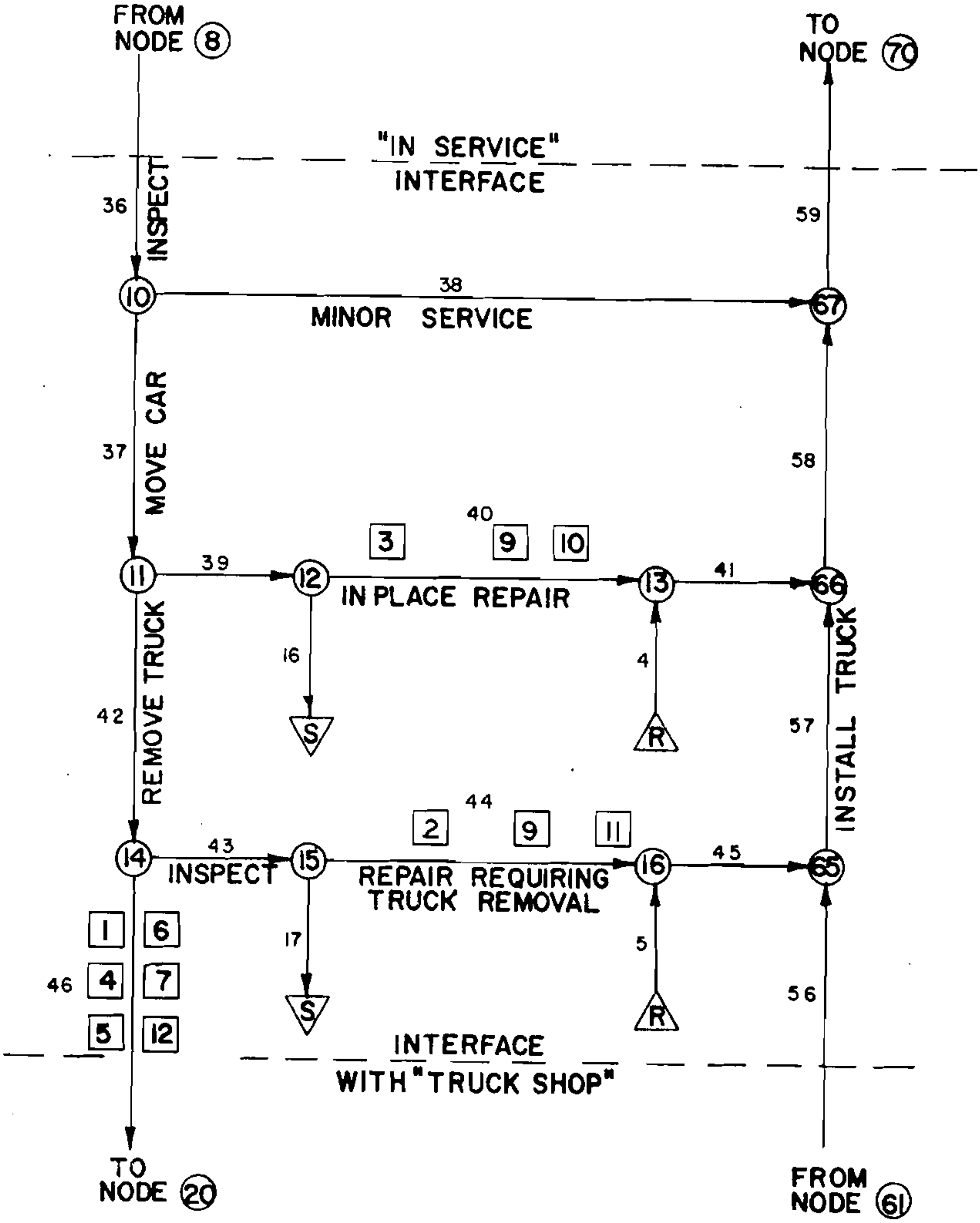
It can be observed from the Metroliner and Amcoach schematics that the Metroliner schematic is the more complex. There are two reasons for this. The first reason is that the Metroliner truck has more components (e.g., motors, gearboxes). The second reason is that the Metroliner maintenance facility is complex - maintenance is performed on nearly all truck components. The Amcoach facilities are not as complex (as concern the truck) - inspection and maintenance are performed in one track area and only on certain components. (Amcoach servicing involves replacement of brake components, suspension components, or wheel-axle assemblies. Secondary suspension springs and air bags are replaced by jacking up the car body - the truck is not removed from the car. If wheel-axle assemblies are defective, the entire assembly is removed and replaced with another wheel set. The wheel set includes the wheels, bearings, axle, and disk brake plates.)

An attempt has been made to keep the Metroliner and Amcoach schematics as similar as possible. Such similarity aids in the preparation of data and in the interpretation of results. For this reason, the same node numbers and path numbers have been used in similar places on the two diagrams. Also, the same numbers have been used to identify corresponding components in the two trucks.




"IN SERVICE" SCHEMATIC

FIGURE 3.6 METROLINER SCHEMATIC




"CAR SHOP" SCHEMATIC

FIGURE 3.7 METROLINER SCHEMATIC

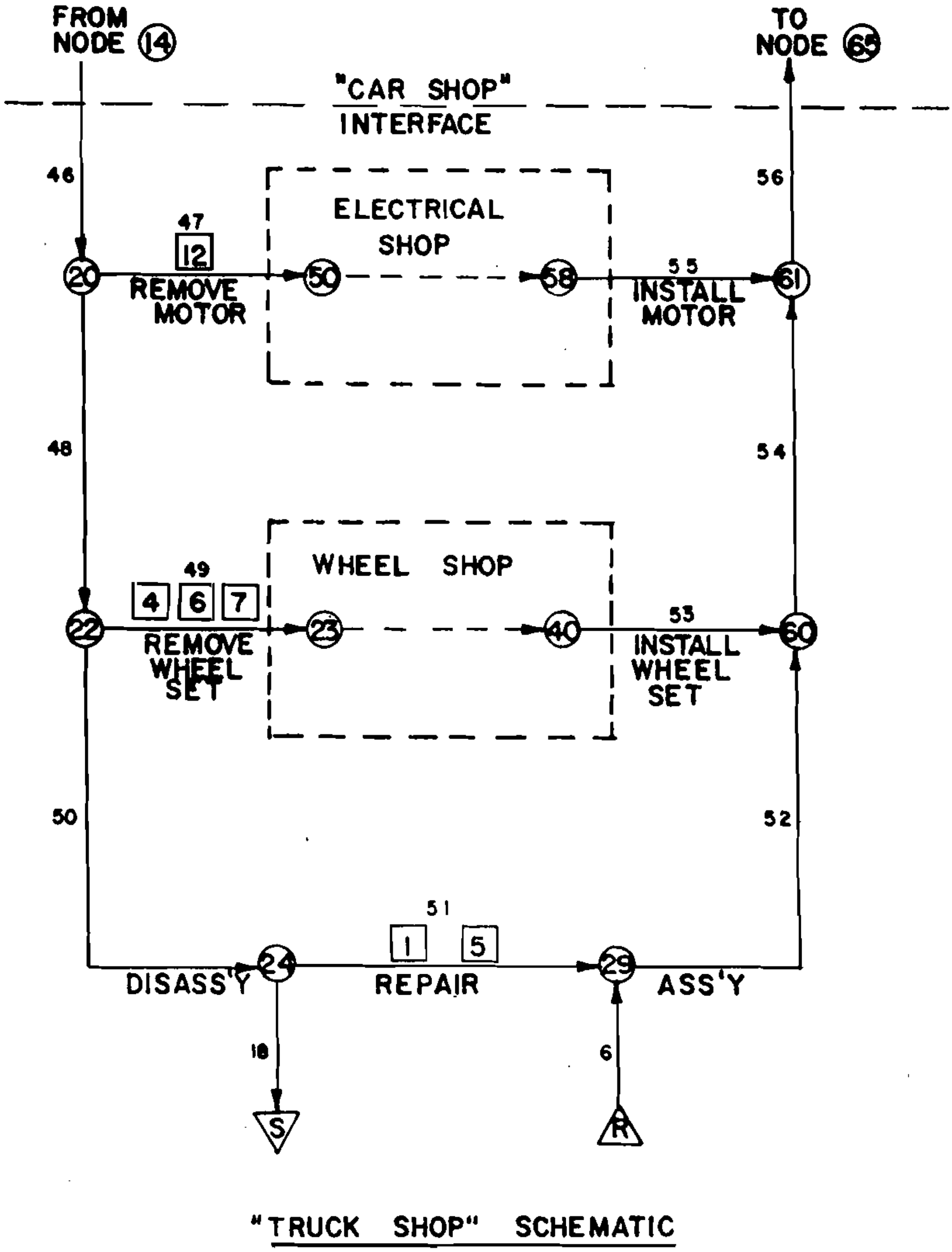
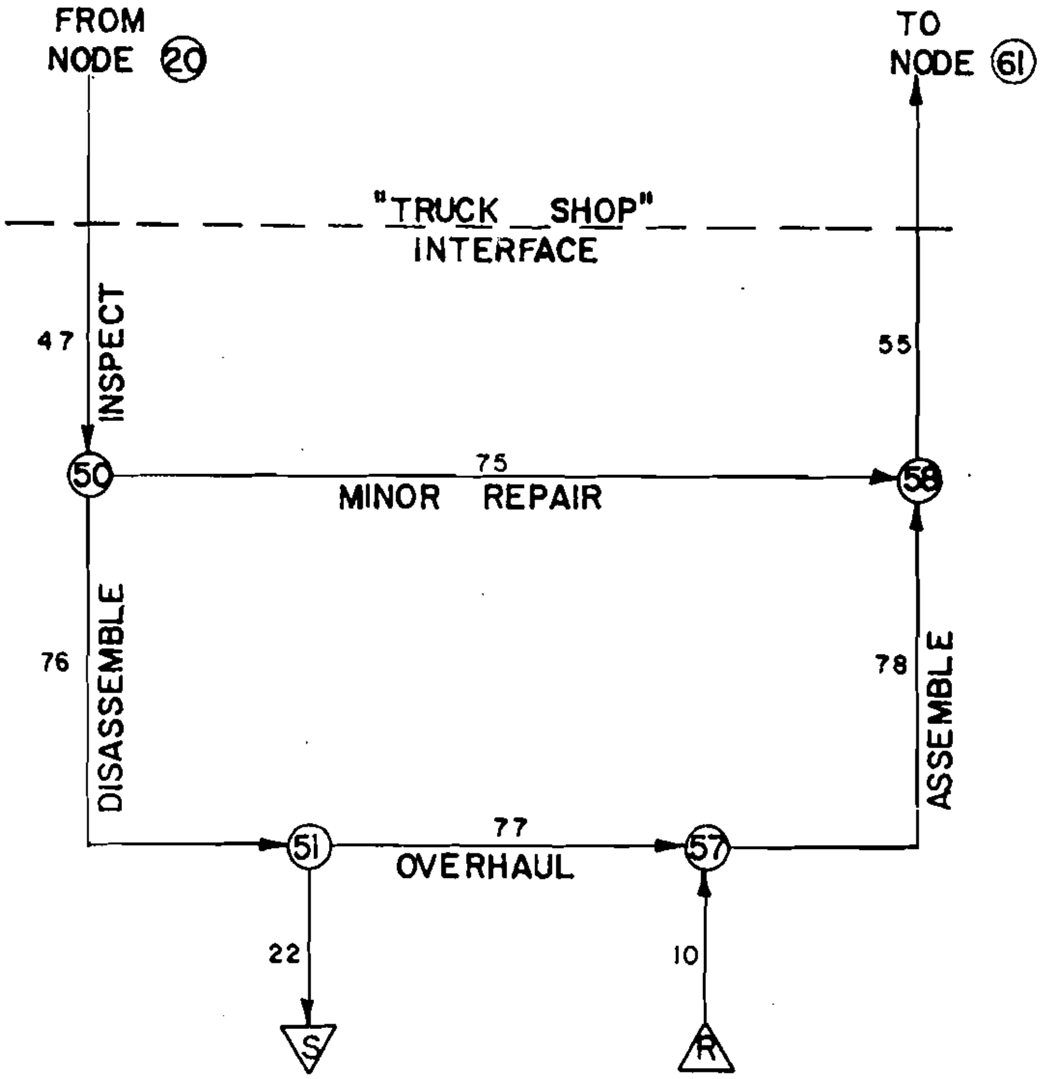



FIGURE 3.8 METROLINER SCHEMATIC




"ELECTRICAL SHOP" SCHEMATIC

FIGURE 3.9 METROLINER SCHEMATIC

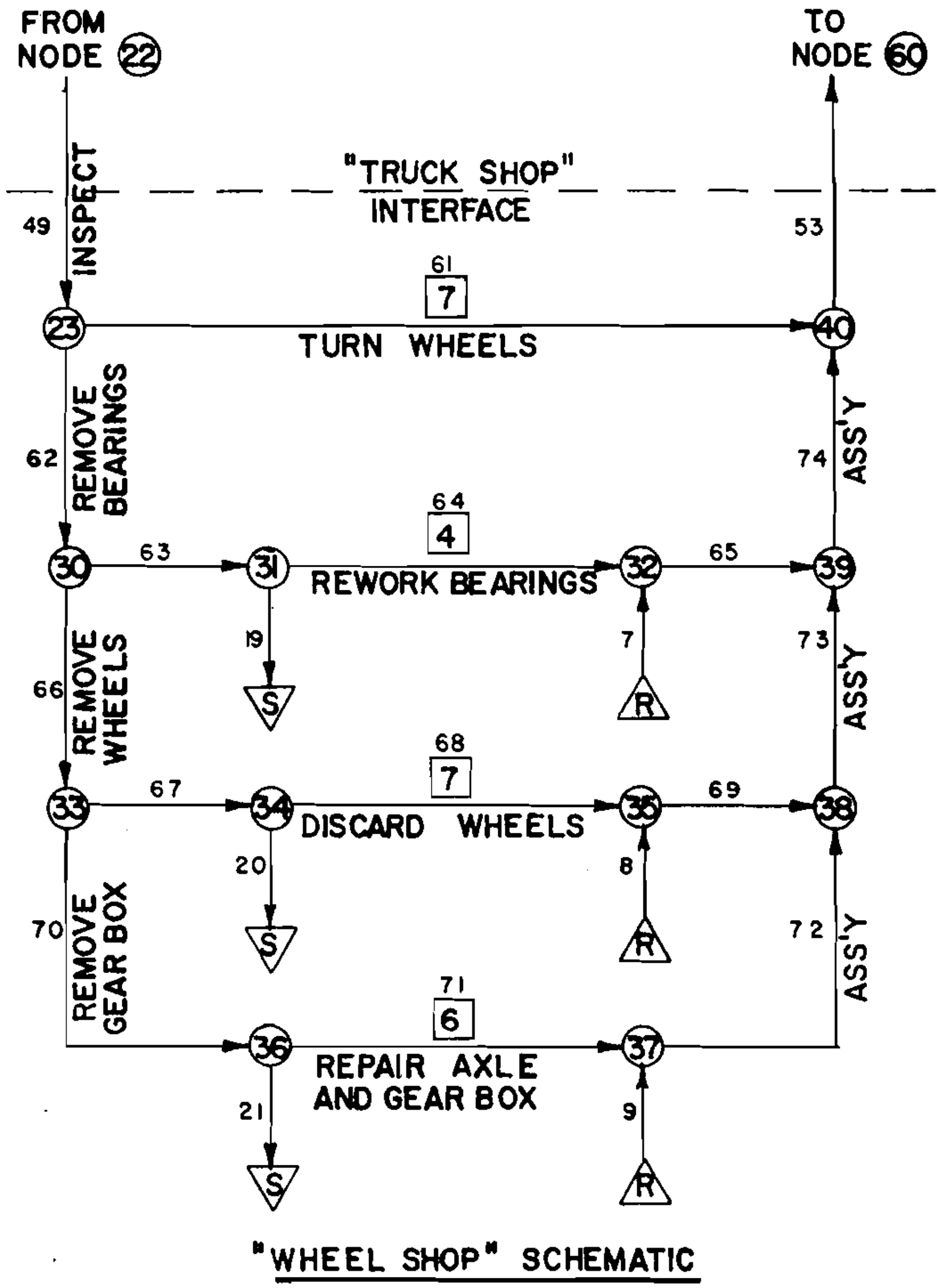



FIGURE 3.10 METROLINER SCHEMATIC

TABLE 3.2

COMPONENT DESIGNATION FOR METROLINER

| | |
|---|---|
| 1 | PRIMARY SPRINGS |
| 2 | SECONDARY SPRINGS |
| 3 | DAMPERS |
| 4 | BEARINGS |
| 5 | FRAMES |
| 6 | AXLES/GEAR BOXES |
| 7 | WHEELS |
| 8 | BRAKES |
| 9 | PNEUMATIC SYSTEMS |
| 10 | ALTERNATORS |
| 11 | BOLSTERS |
| 12 | MOTORS |

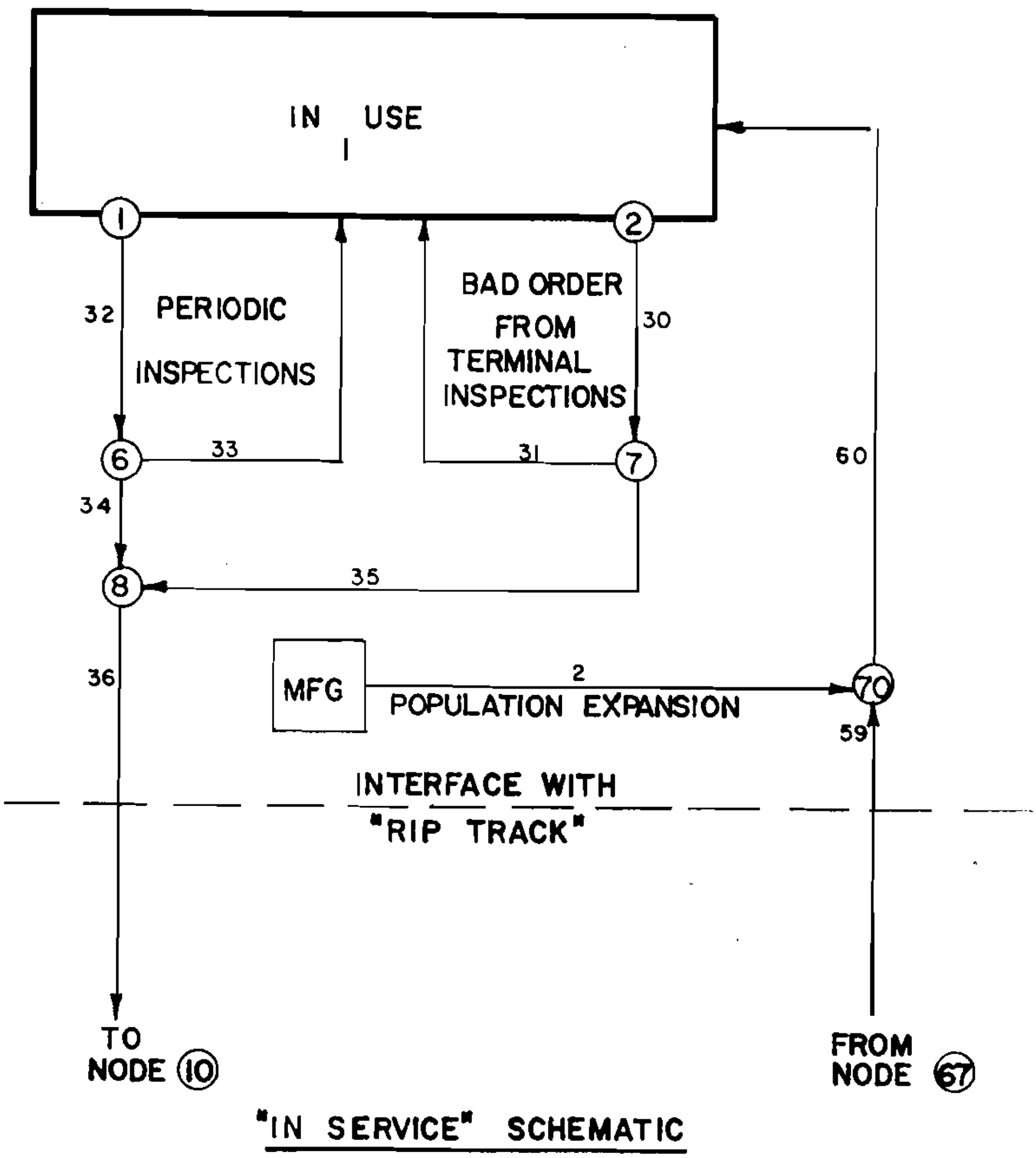



FIGURE 3.11 AMCOACH SCHEMATIC

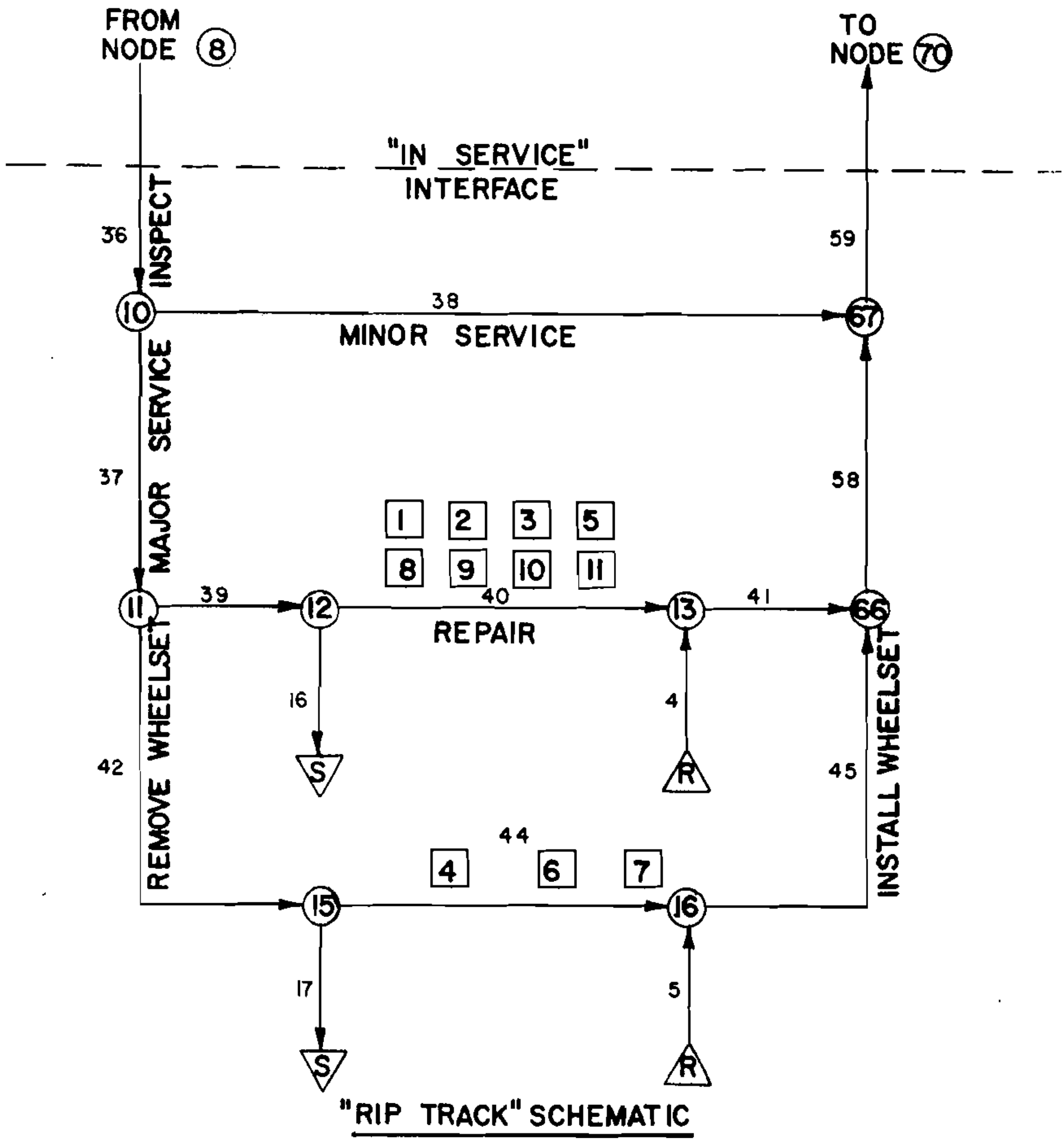



FIGURE 3.12 AMCOACH SCHEMATIC

TABLE 3.3

COMPONENT DESIGNATION FOR AMCOACHES

| | |
|---|---|
| 1 | PRIMARY SPRINGS (RUBBER RINGS) |
| 2 | SECONDARY SPRINGS (STEEL AND AIR BAGS) |
| 3 | DAMPERS |
| 4 | BEARINGS |
| 5 | SIDE FRAMES (WEAR PADS) |
| 6 | AXLES/BRAKE DISKS |
| 7 | WHEELS |
| 8 | BRAKE ASSEMBLIES |
| 9 | PNEUMATIC SYSTEMS (AIR BAGS & LEVELING VALVES) |
| 10 | DECELOSTATS & SPEED SENSORS |
| 11 | BOLSTERS |

## 4. DATA COLLECTION AND BASE CASE ANALYSES

In this section, the data used to produce the base case analyses for the Metroliner and Amcoach trucks are presented. The section also presents the base case analyses which are produced by the SCM.

The data to be collected for a given truck include maintenance intervals, inspection practices, unit costs, and component reliabilities. However, the data available for one type of truck need not be the same as those available for another truck. Maintenance actions and record-keeping can vary among trucks even within a given operating organization such as Amtrak. As a result, the data which can be obtained for a truck can be identified only after some study of the truck and its maintenance actions. From such a data set, the values of the parameters needed to run the model must be derived. This requires a flexible technique for determining the parameter values so that a variety of available primary data can be utilized for the computer model. Such a technique is described in Section 4.1.

Section 4.2 presents the data obtained for the two trucks. The majority of those data are the unit cost data and the flow-decision data. The section also gives the resulting values of the parameters used in the simulation model for each truck.

The base case analysis for each truck is given in Section 4.3.

### 4.1 Determination of Values for the SCM Parameters from Available Data

Section 3 considered the data that are needed in order to produce a base case analysis. These data are the values of the unit costs for each path, the decision parameters at each branch node, and the number, representative age, and quality (proportion defective) for each component in the population.

Of these data requirements, the unit costs are the easiest to obtain and the most straightforward to describe. Typical unit costs are the cost to turn a wheel, the cost to inspect a truck for specific defects, the cost to

For a component which is part of a distinguishable subassembly, the program estimates the proportion (of that component's arriving units) which branches to the outgoing path intended for defective units. This proportion applies only to that component; i.e., the decision is not coupled to others for the subassembly. However, the proportion satisfies a constraint. The constraint is that the coupling of the decision for this component with those for the other components in the subassembly produces the known flow proportion for the entire subassembly at the node. The estimate is made by treating all components in the subassembly as equally likely to cause the subassembly to be sent on the outgoing path intended for defectives. If not all the components in the subassembly are equally likely to cause this, that estimate can be overridden.* To override the estimate, the user specifies the extent to which some of the components in the subassembly control the decision made for the entire subassembly at the branch node. At this point, the program contains either the estimated or overridden value (for each component, treated individually, in the subassembly) of the proportion which branches to the path intended for defectives. In either case, the program then uses these values for the individual components in the subassembly to compute values for their decision parameters (C, or D and E values).**

The result of the above technique is that, for each branch node in the schematic diagram, a value of C (or D and E)*** for each component is determined from the available flow data. If a component is not part of a distinguishable subassembly, its C (or D and E) value, is determined directly from the flows and qualities of that component on the paths associated with the node. If a component is part of a distinguishable subassembly its C

---

*An example of such a case is the decision made to send wheelsets to the wheel shop. Typically, this decision is based on the need for wheel maintenance. The bearings and axle then must accompany the wheels to the wheel shop. It is significantly less likely that the bearings or axle will cause a wheelset to be sent to the wheel shop.

**See Section 4.1.1 of this report for a more detailed discussion of this calculation process.

***The decision parameter G (age decision) is not computed by this program and was not used for either the Metroliner or Amcoach trucks. The reason for this is that age-based decisions are generally treated as periodic decisions for which the C decision parameter is employed.

(or D and E) value is determined only in part by the flows and qualities of the subassemblies on the paths associated with the node. Its C (or D and E) value is also determined by the role the component plays in the decision being made at that branch node.

Use of the technique typically starts at nodes in the schematic diagram where some flow and quality data are known. These are frequently nodes associated with scrap paths or with rework paths. The interactive computer program then provides the user with the decision parameter values (for all components) at the node. The program also produces values for the remaining unknown flows and qualities on the paths associated with the node. Using the flows and qualities so determined, the user can proceed to another node. As this other node (the interactive program can work with summation as well as branch nodes), the process is repeated. The result is a node-by-node calculation process which utilizes known path flow and quality data, as well as known decision data, to yield values of all decision parameters at all branch nodes. These decision parameters are then used with the cost data and population data to produce the base case analysis, sensitivity analyses, and simulations.

### Details of the Calculation Process Used to Compute Decision Parameter Values from Flow and Quality Data

The calculation process used to compute the C, or D and E values from flow and quality data employs the relationships given in Section 3.3. The situation in which the component is not part of an identifiable subassembly is considered first. The situation in which the component is part of such a subassembly is then discussed.

When a flow of a component, say component k, arrives at a branch node, a proportion is directed toward the path intended for defective* units. This proportion can be computed once 2 of the 3 flows associated with the node

*The term "defective" is used merely to identify this outgoing path. By convention, it is labelled path 1 in this section and in Section 3.3.

purchase a new damper or spring, etc. Unit costs generally are given in terms of dollars per component or dollars per subassembly, although any nonlinear cost relationship can be used.* Values for unit costs can be obtained in a number of ways. Purchase prices are determined from vendors or from purchase orders. Labor costs are calculated from the time to do a specific task or set of tasks and generally include appropriate overhead factors. Frequently, standard labor times or rates for particular tasks can be employed.** Shipping costs can be estimated using the distances between maintenance facilities and the mode of transportation employed. Inventory, facility, and delay costs can be produced by using conventional accounting costs and by associating these costs with the components or subassemblies responsible for those costs.

Obtaining values for the decision parameters at each branch node is more difficult. These decision parameters are the C, D, E, K$, and G quantities described in Section 3.3. In general, these parameters define, for the units arriving at a branch node, that proportion which branches to one of the two departing paths. For some branch nodes, these proportions may be obtained directly from the primary data. As an example, inspections are generally given periodically (at fixed intervals of time) to each truck in a fleet. This process is equivalent to requiring that a known percentage of the truck population or of an arriving path to a branch node branches to the inspection path. Numerically, if each truck in a fleet of 120 trucks is inspected monthly, and if all trucks arrive once a day at the place where those to be inspected are selected, then the proportion of those arriving which is inspected (the "C" value) is $\frac{120\text{x}12}{120\text{x}365} = 0.0329$.

For many branch nodes, the values of the decision parameters cannot be obtained directly from the available data. In such cases, the number of components and their quality (proportion defective) in some paths at a specific time may be known. However, the decisions made at the branch nodes which produced these component flows are not known. As an example, generally the number of components scrapped or reworked is known. Also, the proportion of these components which is defective at scrapping or prior to rework is

*An example of such a nonlinear relationship is a unit cost dependence on the number of units purchased or processed.

**An example is the CRB (Car Repair Billing) System used by the rail freight industry.

known. However, the D and E values at the upstream branch nodes which produced the scrap flows are not known. To complicate matters, it is possible that component flows may be known on some, but not all, paths between the input path to a maintenance facility and the scrap path from that facility. As an example, the number of wheels turned in the wheel shop may be known, but the number of wheels associated with other operations in the wheel shop may not be known.

There is a further complication. At many branch points in the schematic diagram, it is necessary that complete subassemblies depart on the outgoing paths. Such a case exists, for instance, for the branch node* just prior to the wheel shop. In that case, complete wheelsets (e.g., axle, bearings, and wheels) must leave the node in order to arrive as complete wheelsets at the wheel shop. For these branch nodes, values of decision parameters for the individual components must be produced from primary data consisting of flows and qualities for the complete subassemblies. (It is the decision made for each component of the subassembly which, when coupled with the decisions made for the other components of the subassembly, determines the number of subassemblies on each outgoing path.)

The above considerations suggests the need for a flexible technique to compute the values of the nodal decision parameters for situations in which the primary data consist of flows and qualities. This technique has been developed. It consists of a BASIC computer program (Appendix A) for operation interactively on a minicomputer. The computer program allows the user to enter known flows and qualities for paths surrounding a node. The program then computes the remaining unknown flows and qualities on these paths. If the component being considered at the node is not part of a subassembly, its C, or D and E values are computed directly. In this relationships given in Section 3.3 are used.** If the component being considered is part of a distinguishable subassembly, the following method is employed.

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*Node 22 for the Metroliner

**See Section 4.1.1 of this report for a more detailed discussion of this calculation process.

are known. If the decision for the component at the node is a C decision (a decision not affected by the quality of arriving units), the proportion is simply the value of C. In the notation of Section 3.3,

$$C_k = \frac{N_{1k}}{N_k}$$

If the decision is a D and E decision (a decision affected by the quality — proportion defective — of arriving units), then the proportions of the units which are defective in 2 of the 3 flows must be known. In this case, the remaining quality can be computed from

$$Q_k N_k = Q_{1k} N_{1k} + Q_{2k} N_{2k} \tag{2}$$

which is the statement of conservation of defective components at the node. The D and E values are

$$D_k = \left(\frac{Q_{1k}}{Q_k}\right) \frac{N_{1k}}{N_k} = \left(\frac{Q_{1k}}{Q_k}\right) C_k \tag{3}$$

$$E_k = \left(\frac{1-Q_{1k}}{1-Q_k}\right) \frac{N_{1k}}{N_k} = \left(\frac{1-Q_{1k}}{1-Q_k}\right) C_k$$

These expressions can be obtained from

$$\frac{N_{1k}}{N_k} = D_k Q_k + E_k (1-Q_k)$$

$$Q_{1k} = \frac{D_k Q_k}{D_k Q_k + E_k (1-Q_k)}$$

which were given in Section 3.3.

When the component is part of an identifiable subassembly, the interrelationship of the component with the remaining components of the subassembly must be considered. The flow and quality data are those for the complete subassemblies; nevertheless, the C (or D and E) values for the individual components (as unaffected by the remaining components of the subassembly) must be determined. To do so, the proportion of subassemblies which branch to path 1 is first computed. This proportion is $C^*$. From Section 3.3

$$C^* = 1 - \prod_K (1-C_k)$$

where $C_k$ is the proportion for component k branching to path 1. This proportion is that prior to the coupling of the decision for component k with the remaining components in the subassembly. The various $C_k$ values can all be equal in the event that all components in the subassembly are equally likely to cause the subassembly to branch to path 1. In that event, $C_k$ is given by

$$C_k = 1-(1-C^*)^{1/K}$$

for all k components. If certain components dominate the decision at the node, then those $C_k$ values can be specified (the above value of $C_k$ can be overridden), subject to the constraint that $C^*$ (which is known) is equal to $\prod_K(1-C_k)$. The remaining steps for obtaining the values of $C_k$ (or $D_k$ and $E_k$) are the same as those for components which are not part of an identifiable subassembly. Specifically, if the decision for subassembly component k is a C decision, the value of $C_k$ is that already determined. If the decision is a D and E decision, the qualities on 2 of the 3 nodal paths for component k are needed. The remaining quality is computed using Equation (2) and the $D_k$ and $E_k$ values are computed using relationships (3).

## 4.2 Data for the Metroliner and Amcoach Trucks

This section presents the data for the Metroliner and for the Amcoach trucks. Because the two trucks are dissimilar in construction, population size and maintenance actions, these data are presented separately for each truck. In Section 4.2.1, the Metroliner truck is considered. The Amcoach truck is considered in Section 4.2.2.

### 4.2.1 Metroliner Data

The data used for the Metroliner truck were obtained primarily from the Wilmington (Delaware) Metroliner Facility. This facility was visited during the contract. Numerous telephone conversations with members of the maintenance staff took place. In addition, letters were written to appropriate members of the staff.

The results of the communications were data values for various facets of the Metroliner truck maintenance operations. These data included:

- costs for component purchase
- amount of labor required for various actions
- costs for certain maintenance operations (e.g., traction motor overhaul)
- schedules for maintenance of the various components
- estimates for the inspection rate of the cars (i.e., number of cars inspected per month)
- estimates of the mileage travelled annually by a typical car
- the average number of cars in the fleet and the number of cars out of service at any time
- for some components, the number of components replaced annually and/or the expected life of the components.

In addition to the information obtained from Wilmington, additional data were obtained from the AAR. These data consisted primarily of the costs for new components, the scrap value for components, and a representative hourly labor rate.

The data collected were employed to compute values for those cost model parameters required for a base case analysis. Tables 4.1a and 4.1b present the data which were used in this computation. Table 4.1a lists each component, its designation number, and the number of units for the component

TABLE 4.1a

METROLINER INPUT DATA

POPULATION SIZE AND UNIT VALUES

| Component Designation No. | Name of Component | # In System | New Cost (Each) | Scrap Value (Each) | Data Source and Remarks |
|---|---|---|---|---|---|
| 1 | Primary Springs | 488 | $ 200 | $ 1 | AAR Office Manual Job Codes 3900-3968 |
| 2 | Secondary Springs | 488 | 150 | 1 | AAR Office Manual Job Codes 3900-3968 |
| 3 | Dampers | 488 | 50 | 1 | Estimation from Metroliner maintenance staff |
| 4 | Bearings | 488 | 150 | 6 | AAR Office Manual Job Codes 2800-2816 |
| 5 | Frames | 122 | 10,000 | 250 | Est. New Cost, Scrap at 25 cents/lb - 1000 lbs. |
| 6 | Axles/Gear Boxes | 244 | 2,500 | 25 | AAR Office Manual Job Codes 3250-3288 |
| 7 | Wheels | 488 | 200 | 20 | AAR Office Manual Job Codes 3005-3180 |
| 8 | Brakes | 488 | 8 | 0 | AAR Office Manual Job Code 1830 |
| 9 | Pneumatics | 122 | 250 | 0 | Estimation from Metroliner maintenance staff |
| 10 | Alternators | 122 | 50 | 0 | Estimation from Metroliner maintenance staff |
| 11 | Bolsters | 122 | 1,000 | 20 | AAR Office Manual Job Code 3500-3580 |
| 12 | Motors | 488 | 18,000 | 200 | Estimation from Metroliner maintenance staff |

TABLE 4.1b

METROLINER INPUT DATA — ANNUAL MAINTENANCE COSTS AND FLOWS

| Computer Maintenance Path | CP #* | Description | Annual Component Flow** Number | Proportion Defective | Number Defective | Unit Path Cost | Data Source and Remarks (Rework Labor at $17.27/hr.) Estimates from Metroliner Maintenance Staff Unless otherwise Noted |
|---|---|---|---|---|---|---|---|
| 4 | 3 | New dampers | 278 | 0 | — | — | Dampers replacee (reworked) every two years |
| | 10 | New alternators | 67 | 0 | — | — | Alternators replaced (reworked) every two years |
| 5 | 2 | New primary springs | 92 | 0 | — | — | Replace primary spring every five years |
| | 9 | New pneumatics | 39 | 0 | — | — | Replace air bags every three years |
| 6 | 1 | New secondary springs | 92 | 0 | — | — | Replace secondary springs every five years |
| 7 | 4 | New roller bearings | 182 | 0 | — | — | Replace bearings every three years, about 500,000 miles. AAR Office Manual Job Codes 2800 - 2816 |
| 8 | 7 | New wheels | 479 | 0 | — | — | See path 20. |
| 9 | 6 | Axles/Gear boxes | 50 | 0 | — | — | Rework and/or replace axle/gear box assembly every five years |
| 11 | 8 | New brake shoes | 19589 | 0 | — | — | Replace brake shoes every 4000 miles*** |
| 16 | 3 | Scrap dampers | 278 | 1 | — | — | Scrap flows are replaced by flows of new units |
| 17 | 2 | Scrap secondary springs | 92 | 1 | — | — | " " " " " " " " " |

* CP # refers to truck component designation numbers (See Table 4.1a)

** Dashes indicate that quantity not used as an input data value or value given elsewhere in Table 4.1a or 4.1b.

*** Annual flow incorporates average car mileage of 161,000 miles/year

TABLE 4.1b (cont.)

METROLINER INPUT DATA — ANNUAL MAINTENANCE COSTS AND FLOWS

| Computer Maintenance Path | CP #* | Description | Annual Component Flow** Number | Proportion Defective | Number Defective | Unit Path Cost | Data Source and Remarks (Rework Labor at $17.27/hr.) Estimates from Metroliner Maintenance Staff Unless otherwise Noted |
|---|---|---|---|---|---|---|---|
| 18 | 1 | Scrap primary springs | 92 | 1 | — | — | Scrap flows are replaced by flows of new units |
| 19 | 4 | Scrap roller bearings | 182 | 1 | — | — | " " " " " " " " " |
| 20 | 7 | Scrap wheels | 479 | 685 | — | — | Bad wheels and good mate wheels are discarded on this path. Majority of discarded wheels are defective. Remainder are mate wheels. Discard rate is 40 per month. Scrap flows are replaced by flows of new units |
| 21 | 6 | Scrap axle/gear boxes | 50 | 1 | — | — | " " " " " " " " " |
| 23 | 8 | Total brake shoe maintenance | 19589 | 1 | — | — | " " " " " " " " " |
| 30 | All | Daily terminal inspection | 32122 | — | — | 25000 | Daily terminal enspections of 44 cars. Estimate of total system cost for these inspections. |
| 32 | All | Monthly terminal inspections | 1464 | — | — | 25000 | Monthly inspections of 61 cars. Estimate of total system cost for these inspections. |

* CP # refers to truck component designation numbers (See Table 4.1a).

** Dashes indicate that quantity not used as an input data value or value given elsewhere in Table 4.1a or 4.1b.

TABLE 4.1b (cont.)

METROLINER INPUT DATA — ANNUAL MAINTENANCE COSTS AND FLOWS

| Computer Maintenance Path | CP #* | Description | Annual Component Flow** Number | Proportion Defective | Number Defective | Unit Path Cost | Data Source and Remarks (Rework Labor at $17.27/hr.) Estimates from Metroliner Maintenance Staff Unless otherwise Noted |
|---|---|---|---|---|---|---|---|
| 36 | 1 | Incoming maintenance facility inspections | 6980 | — | — | 1.44 | 5 minutes labor on each spring**** |
| | 2 | ↓ | 6980 | — | — | .36 | 5 minutes labor for four springs**** |
| | 3 | | 6980 | — | — | 1.44 | 5 minutes labor each damper**** |
| | 5 | | 1745 | — | — | 4.32 | 15 minutes labor each frame**** |
| | 7 | | 6980 | — | — | 2.88 | 10 minutes labor each wheel**** |
| | 9 | | 1745 | — | — | 1.44 | 5 minutes labor each pneumatic system**** |
| | 10 | | 1745 | — | — | 2.30 | 8 minutes labor each alternator**** |
| | 11 | | 1745 | — | — | 5.76 | 20 minutes labor each bolster**** |
| 38 | All | Minor service | 0 | — | — | — | Path not used |
| 42 | 5 | Disassemble trucks for rework | — | — | — | 77.72 | Single truck removed from car. Trucks exclusive of components 3, 9, 10. 6 men for 3/4 hr. |
| 43 | 2 | Rework secondary springs | — | — | 371 | 207.24 | Disassemble/reassemble spring components 4 men 3 hr. 3/4 of all springs maintained or discarded each year. |

* CP # refers to truck component designation numbers (See Table 4.1a).

** Dashes indicate that quantity not used as an input data value or value given elsewhere in Table 4.1a or 4.1b.

*** Annual flow incorporates average car mileage of 161,000 miles/year.

**** Flow based on estimate of 2-3 cars per day serviced at maintenance facility.

TABLE 4.1b (cont.)

METROLINER INPUT DATA — ANNUAL MAINTENANCE COSTS AND FLOWS

| Computer Maintenance Path | CP #* | Description | Annual Component Flow** Number | Proportion Defective | Number Defective | Unit Path Cost | Data Source and Remarks (Rework Labor at $17.27/hr.) Estimates from Metroliner Maintenance Staff Unless otherwise Noted |
|---|---|---|---|---|---|---|---|
| | 9 | Rework pneumatics (air bags) | — | — | — | 60.00 | Disassemble/reassemble bad air bags (Estimate 3.5 man hour) |
| | 11 | Rework bolsters | — | — | 93 | 207.24 | Disassemble/reassemble bolster. 4 men 3 hours. 3/4 of all bolsters receive maintenance each year. |
| 47 | 12 | Motor disassembly | — | — | — | 51.81 | Disassemble motor 3 hours. |
| 49 | 4 | Inspect bearings | — | — | — | 0.72 | 5 min per pair (must look at all bearings) |
| | 6 | Inspect axle/gear boxes | — | — | — | 8.64 | 1/2 hr. each assembly (must look at all axle/gear boxes) |
| | 7 | Inspect wheels | — | — | — | 2.88 | 10 min. per wheel (must look at all wheels) |
| 61 | 7 | Turn wheels if needed | 4380 | — | — | 6.48 | Labor to turn. 3/4 hr. per pair. Turn 6 pair of wheels per day. |
| 62 | 4 | Remove bearings | 479 | — | — | 4.32 | 15 min. each. Bearings from axles with wheel scrapped. |
| 64 | 4 | Rework roller bearings | — | — | — | 69.08 | Clean and reassemble all in path. 4 hr/bearing. |

* CP # refers to truck component designation numbers (See Table 4.1a).

** Dashes indicate that quantity not used as an input data value or value given elsewhere in Table 4.1a or 4.1b.

TABLE 4.1b (cont.)

METROLINER INPUT DATA — ANNUAL MAINTENANCE COSTS AND FLOWS

| Computer Maintenance Path | CP #* | Description | Annual Component Flow** Number | Proportion Defective | Number Defective | Unit Path Cost | Data Source and Remarks (Rework Labor at $17.27/hr.) Estimates from Metroliner Maintenance Staff Unless otherwise Noted |
|---|---|---|---|---|---|---|---|
| 66 | 7 | Remove wheels | — | — | — | 4.32 | Remove wheels for discard 1/4 hr. |
| 68 | 6 | Carry wheelset axles/ gear boxes | — | — | — | 4.32 | Preparation axle/gear box for new wheels, 1/4 hr. |
| 70 | 6 | Disassemble axle/gear boxes | — | — | — | 17.27 | Remove gear box 1 hr. |
| 71 | 6 | Axle/gear box repair | 72 | — | — | 89.01 | 5-1/4 hr. labor only. Parts (new axles) costs are on paths 9 and 21. Gear boxes reworked typically each 3 years (about 500,000 miles) |
| 72 | 6 | Reassembly | — | — | — | 17.27 | Reassemble axle/gear box subassembly 1 hr. |
| 73 | 7 | Remount wheels on axles | — | — | — | 4.32 | Remount wheels (1/4 hr.) |
| 75 | 12 | Motor maintenance | 230 | 1 | — | 100.00 | Minor motor maintenance. Couplers, brushes, 3 hrs. + parts to equal $100 per repair. Nearly all motors receive minor maintenance each year. |
| 77 | 12 | Motor overhaul | 76 | 1 | — | 2000.00 | Major motor overhaul. Estimate $2000 per motor overhaul. Major overhaul approximately every three years. |

* CP # refers to truck comp nent designation numbers (See Table 4.1a).

** Dashes indicate that quantity not used as an input data value or value given elsewhere in Table 4.1a or 4.1b.

in the Metroliner fleet. In the remaining three columns, the table also lists the unit cost for each component, its scrap value, and the source of these two pieces of cost data.

Table 4.1b gives the remaining data used. This table is organized by path number, given in the left-hand column. Each path for which data were employed is listed. In the second column (from left), the component having associated data is shown, followed in the third column by a description of the event affecting the component in that path. The next column gives the annual flow of units for that component, the proportion of the flow defective, and the annual flow of defective units for that component.* Values are given only when the quantity is an input datum -- dashes indicate that the quantity is not used as an input datum or that its value is given elsewhere in the two tables. Unit path costs are given in the next column. These costs are in dollars per unit. Dashes have the same meaning as for the preceding column. Sources for the data values are presented in the right-hand column. Unless otherwise noted, the information in this column was obtained from the Wilmington maintenance staff.

From the data given in Tables 4.1a and 4.1b, values of those cost model parameters sufficient to produce a base case analysis were obtained. These parameters are the unit path costs, the quantities C, D, E, and K$ (see Section 3 for a description of these quantities), and the base case values of the population (or state) variables. The unit path costs are those in Tables 4.1a and 4.1b and are applied, as appropriate for each component, to the flow of all units in a path or to the flow of defective units in a path.** The values for parameters C, D, E, and K$ are obtained by using the technique described in Section 4.1.1. The resulting C, D, E, and K$ parameter values are given in Table 4.2. This table gives the number for each branch node (decision node) a sequential numbering of the branch nodes, the components for which parameter values are applied,

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*These three items are not independent. The second number (the "quality") is the ratio of the third number to the first number.

**An example in which the costs are applied to the flow of all units in a path is an inspection operation (both good and defective units must be inspected). An example in which the costs are applied to the flow of defective units in a path is a repair operation (generally, only the defective units must be repaired).

TABLE 4.2

VALUES OF THE PARAMETERS C, D, E, and K$

FOR THE METROLINER

| Node No. | Branch Node No. | Component No. | Identifiable Subassembly* | C** | D | E |
|---|---|---|---|---|---|---|
| 1 | 1 | All | K$ | 12.000 | | |
| 2 | 2 | All | K$ | 263.000 | | |
| 3 | 3 | All | K$ | 263.000 | | |
| 4 | 4 | 8 | | | 1.000 | 0.000 |
| 6 | 5 | All | K$ | 0.05 | | |
| 7 | 6 | All | K$ | | 0.045 | $5.0 \times 10^{-7}$ |
| 10 | 7 | All | K$ | | 1.000 | 0.870 |
| 11 | 8 | 1 | K$ | | 1.000 | 0.999 |
| | | 2 | K$ | | 1.000 | 0.999 |
| | | 4 | K$ | | 1.000 | 0.999 |
| | | 5 | K$ | | 1.000 | 0.999 |
| | | 6 | K$ | | 1.000 | 0.999 |
| | | 7 | K$ | | 1.000 | 0.994 |
| | | 8 | K$ | 0 | | |
| | | 9 | | | 0.354 | 0 |
| | | 11 | K$ | | 1.000 | 0.999 |
| | | 12 | K$ | | 1.000 | 0.999 |
| 12 | 9 | 3 | | | 0.750 | 0.000 |
| | | 10 | | | 1.000 | 0.000 |
| 14 | 10 | 1 | K$ | | 1.000 | 0.993 |
| | | 4 | K$ | | 1.000 | 0.993 |
| | | 5 | K$ | | 1.000 | 0.993 |

* The component in part of an identifiable subassembly at this node if K$ parameter is used.

** Value of C for a component at a branch node is zero if a value is not given in the table for C, D, or E.

TABLE 4.2 (cont.)

VALUES OF THE PARAMETERS C, D, E, AND K$
FOR THE METROLINER

| Node No. | Branch Node No. | Component No. | Identifiable Subassembly | C | D | E |
|---|---|---|---|---|---|---|
| | 10 | 6 | K$ | | 1.000 | 0.993 |
| | | 7 | K$ | | 1.000 | 0.976 |
| | | 12 | K$ | | 1.000 | 0.992 |
| 15 | 11 | 2 | | | 0.250 | 0.000 |
| | | 9 | | | 1.000 | 0.000 |
| 20 | 12 | 1 | K$ | | 1.000 | 0.995 |
| | | 4 | K$ | | 1.000 | 0.996 |
| | | 5 | K$ | | 1.000 | 0.996 |
| | | 6 | K$ | | 1.000 | 0.996 |
| | | 7 | K$ | | 1.000 | 0.984 |
| | | 12 | | | 0.000 | 1.000 |
| 22 | 13 | 4 | K$ | | 1.000 | 0.256 |
| | | 6 | K$ | | 0.372 | 0.192 |
| | | 7 | K$ | | 0.992 | 0.240 |
| 23 | 14 | 4 | K$ | | 1.000 | 0.014 |
| | | 6 | K$ | | 1.000 | 0.001 |
| | | 7 | K$ | $1.317 \times 10^{-5}$ | | |
| 24 | 15 | 1 | | | 0.250 | 0.000 |
| 30 | 16 | 6 | K$ | 1.000 | | |
| | | 7 | K$ | 1.000 | | |
| 31 | 17 | 4 | | | 1.000 | 1.000 |
| 33 | 18 | 6 | | | 1.000 | 0.000 |
| 34 | 19 | 7 | | 1.000 | | |
| 36 | 20 | 6 | | 0.410 | | |

TABLE 4.2 (cont.)

VALUES OF THE PARAMETERS C, D, E, and K$

FOR THE METROLINER

| Node No. | Branch Node No. | Component No. | Identifiable Subassembly | C | D | E |
|---|---|---|---|---|---|---|
| 50 | 21 | 12 | | | 0.250 | 0.000 |
| 51 | 22 | 1 | | 0.000 | | |

| Component Number | Population Size | Quality (Proportion Defective) |
|---|---|---|
| 1 | 488 | 0.030 |
| 2 | 488 | 0.030 |
| 3 | 488 | 0.030 |
| 4 | 488 | 0.015 |
| 5 | 122 | 0.025 |
| 6 | 244 | 0.026 |
| 7 | 488 | 0.306 |
| 8 | 488 | 0.152 |
| 9 | 122 | 0.036 |
| 10 | 122 | 0.022 |
| 11 | 122 | 0.030 |
| 12 | 244 | 0.050 |

and the decision data. The base case values of the population variables include, for each component, the population size, representative age*, and quality (proportion defective). The population size for each component was already given in Table 4.1a. The quality for each component is obtained along with the decision parameter values C, D, E, and K$. These quality values are given, along with a repetition of the population size, at the end of Table 4.2.

### 4.2.2 Amcoach Data

Data from the Amcoach truck were obtained from several sources. One source was the Budd Company, the subcontractor to Shaker Research for this work. Budd provided data for many components concerning maintenance intervals, maintenance labor and actions, inspection requirements, expected mileage, and replacement costs. Additional information was obtained directly from Amtrak. The 30th Street maintenance facility in Philadelphia was visited. This visit concerned the procedure for Amcoach maintenance and the records that result from that maintenance.** Also, rough data values were obtained during the visit. It was learned that only a portion of the Amfleet cars are maintained in Philadelphia; systemwide data could readily be obtained only through a newly installed computerized system. This system MAP (Maintenance Analysis Program), was therefore also used as a data source. Three months of repair records were obtained from the computer.*** These data were compared to the information from Budd and from the visits in order to arrive at the data values used. Discrepancies were resolved through telephone conversations with personnel in the Philadelphia facility.

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*No age decisions (G decisions) are used for the base case analysis of either the Metroliner or Amcoach trucks. Consequently, a value of the representative age for each component is not needed to produce the base case analysis. This value is needed, however, to produce simulations for the two trucks.

**A discussion of Amcoach maintenance and the associated data records is given in Appendix B.

***A typical output page from the Maintenance Analysis Program is given in Appendix B.

The Amcoach truck is represented for the simulation cost model in terms of eleven subsystems (see Section 2). However, the information from Budd and from the MAP included some data on significantly more individual components (approximately 40). As a result, each of these individual components was associated with one of the eleven subsystems for the cost model.

The data used to produce the Amcoach base case analysis are given in Tables 4.3a and 4.3b. These tables correspond to Tables 4.1a and 4.1b for the Metroliner. As for the Metroliner, Table 4.3a gives the component number, name, population size, unit costs, and data sources. Table 4.3b gives, by path and by component, path flow and unit path cost data. Sources and remarks for the data are given in the right-hand column.

The branch node decision parameters, calculated from the data in Tables 4.3a and 4.3b are given in Table 4.4. This table corresponds to Table 4.2 for the Metroliner. As for the Metroliner, the table lists each branch node and its associated node number and gives a decision parameter value for each appropriate component. Where no values are given for a component or where a component is not listed, the C value for that component at that node is zero. At the end of the table, values of the population size and quality (proportion defective) for each component are given.

TABLE 4.3a

AMCOACH INPUT DATA

POPULATION SIZE AND UNIT VALUES

| Component Designation No. | Name of Component | # In System | New Cost (Each) | Scrap Value (Each) | Data Source and Remarks |
|---|---|---|---|---|---|
| 1 | Primary springs (rubber rings) | 3936 | $ 40 | $ 0 | Purchase cost of rubber ring (no labor), estimate* |
| 2 | Secondary springs (steel and air bags) | 1968 | $400 | $ 0 | $200/coil + $200/air bag, estimate |
| 3 | Dampers | 3936 | $ 50 | $ 0 | Estimate |
| 4 | Bearings | 3936 | $ 75 | $ 6 | Cost to replace a bearing with a used bearing that has been re-worked* |
| 5 | Side frames (wear pads) | 1968 | $ 2 | $ 0 | Purchase price of a new wear pad (no labor) |
| 6 | Axles/Brake Disks | 3936 | $400 | $ 1 | Cost of a replacement brake disk*, estimate. Axles designed for infinite life (Budd). |
| 7 | Wheels | 3936 | $200 | $20 | New wheel replacement cost;* AAR Office Manual Job Codes 3005-3180. |
| 8 | Brake Assembly | 3936 | $ 42 | $ 0 | $35 per brake shoe pair, $85 per brake cylinder and cable assembly, Budd estimate. Cylinder and cable assemblies replaced at 1/12 rate of brake shoe pairs (see path 39); i.e., cost is $35 + $85/12. |

*Total cost of a complete wheelset overhaul is approximately $1430.

TABLE 4.3a (cont.)

AMCOACH INPUT DATA

POPULATION SIZE AND UNIT VALUES

| Component Designation No. | Name of Component | # In System | New Cost (Each) | Scrap Value (Each) | Data Source and Remarks |
|---|---|---|---|---|---|
| 9 | Pneumatic system | 1968 | $ 25 | $ 0 | Leveling valve cost, estimate |
| 10 | Speed sensor and decelostat | 1968 | $ 50 | $ 0 | Cost of speed sensor, estimate for typical replacement part |
| 11 | Bolsters | 984 | — | — | Bolster designed for infinite life |

TABLE 4.3b

AMCOACH INPUT DATA — ANNUAL MAINTENANCE COSTS AND FLOWS

| Computer Maintenance Path | CP #* | Description | Annual Component Flow** Number | Annual Component Flow** Proportion Defective | Annual Component Flow** Number Defective | Unit Path Cost | Data Source and Remarks (Labor at $17.27/hr.) |
|---|---|---|---|---|---|---|---|
| 4 | 2 | New air bags - coils | 394 | 0 | — | — | Units must be replaced every 5 years, 492 cars x 4 units per car x 1/5 years = 394 units per year |
| | 5 | New wear pads | 131 | 0 | — | — | Units replaced in 15 years, estimate (492 cars x 4 units per car x 1/5 years = 131 |
| | 8 | New brake assembly | 15744 | 0 | — | — | Shoe pairs replaced every 30,000 miles,*** Budd estimate, 492 cars x 8 pairs per car x 4 times a year = 15744 |
| | 10 | New speed sensor | 394 | 0 | — | — | See path 16 |
| 5 | 1 | Overhauled Journal rubbers | 787 | 0 | — | — | Wheelset overhaul every 5 years (600,000 mi. wheel life estimate),*** 492 cars x 4 units per car x 1/5 years = 787 per year. |
| | 4 | Overhauled Bearing replacement | 787 | 0 | — | — | |
| | 6 | Overhauled Brake discs | 787 | 0 | — | — | |
| | 7 | Overhauled Wheels | 787 | 0 | — | — | |

*CP # refers to truck component deignation numbers (See Table 4.3a).

**Dashes indicate that quantity not used as an input data value or value given elsewhere in Table 4.3a or 4.3b.

***Annual flow incorporates average car mileage of 120,000 miles/year.

TABLE 4.3b (cont.)

AMCOACH INPUT DATA — ANNUAL MAINTENANCE COSTS AND FLOWS

| Computer Maintenance Path | CP #* | Description | Annual Component Flow** Number | Proportion Defective | Number Defective | Unit Path Cost | Data Source and Remarks (Labor at $17.27/hr.) |
|---|---|---|---|---|---|---|---|
| 16 | 2 | Scrap air bags - coils | 394 | 1 | — | — | Scrap flows are replaced with flows of new units. |
| | 5 | Scrap wear pads | 131 | 1 | — | — | |
| | 8 | Scrap brake shoe pads | 15744 | 1 | — | — | |
| | 10 | Scrap speed sensor | 394 | 1 | — | — | Maintenance Analysis Program data |
| 17 | 1 | Sent for overhaul: Journal rubbers | 787 | 0.005 | — | — | Replaced with flow of overhauled wheel-sets. Proportion defective estimated from discussions with maintenance staff and with Budd. Wheel proportion defective based on probable condition*** of wheels after 5 year car mileage. |
| | 4 | Bearing replacement | 787 | 0.010 | — | — | |
| | 6 | Brake Discs | 787 | 0.005 | — | — | |
| | 7 | Wheels | 787 | 0.700 | | | |

*CP # refers to truck component designation numbers (See Table 4.3a).

**Dashes indicate that quantity not used as an input data value or value given elsewhere in Table 4.3a or 4.3b.

***Annual flow incorporates average car mileage of 120,000 miles/year.

TABLE 4.3b (cont.)

AMCOACH INPUT DATA — ANNUAL MAINTENANCE COSTS AND FLOWS

| Computer Maintenance Path | CP #* | Description | Annual Component Flow** Number | Proportion Defective | Number Defective | Unit Path Cost | Data Source and Remarks (Labor at $17.27/hr.) |
|---|---|---|---|---|---|---|---|
| 30 | 2 | Daily inspections: Secondary springs | 718320 | — | — | $0.12 | 12 seconds per coil + 12 seconds/air bag (Flow computed from 492 cars/day x 365 days/yr. x no. of comp./car. Total inspec. time ~ 4 min/truck, Budd estimate.) |
| | 5 | Daily inspections: Side frames | 718320 | — | — | $0.024 | 5 seconds per wear pad |
| | 7 | Daily inspections: Wheels | 1436640 | — | — | $0.0966 | 20 seconds per wheel |
| | 8 | Daily inspections: Brake assembly | 1436640 | — | — | $0.0966 | 20 seconds per brake pad set |
| 32*** | 2 | Inspect secondary springs each month and each 3 months. | 23616 | — | — | $0.96 | 10 min/car for monthly inspection (0.67 times per month) = $0.48 + 20 min/car for 3 month inspection (0.25 times per month) = $0.48. |
| | 5 | Inspect wear pads each 3 months, each 6 months, and each 60 months. | 23616 | — | — | $0.60 | 20 min/car for 3 month inspection (0.15 times per month) = $0.22 + 30 min/car for 6 month inspection (0.15 times per month) = $0.33 + 40 min/car for 60 month inspection (0.017 times per month) = $0.05 |
| | 7 | Inspect wheels each 3 months | 47232 | — | — | $0.54 | 60 min/car (0.25 times per month) = $0.54 |

*CP # refers to truck component designation numbers (See Table 4.3a).

**Dashes indicate that quantity not used as an input data value or value given elsewhere in Table 4.3a or 4.3b.

***Flows computed from 492 x 12 cars/year x no. of components/car. All unit costs for periodic inspections given on the basis of equivalent monthly inspections. Inspection times as estimated by Budd.

(cont.)

TABLE 4.3b

AMCOACH INPUT DATA — ANNUAL MAINTENANCE COSTS AND FLOWS

| | | | Annual Component Flow** | | | | |
|---|---|---|---|---|---|---|---|
| Computer Maintenance Path | CP #* | Description | Number | Proportion Defective | Number Defective | Unit Path Cost | Data Source and Remarks (Labor at $17.27/hr.) |
| *** | 8 | Inspect cables, shoes, etc. each 3 months. | 47232 | — | — | $0.56 | 30 min/car (0.25 times per month) = $0.27 0.5 min/shoe pair (0.25 times per month) = $0.29 |
| | 9 | Inspect fluid level each 3 months. | 23616 | — | — | $0.18 | 10 min/car (0.25 times per month) = $0.18 |
| 36 | All | Incoming flow of trucks requiring service | 39180 | — | — | 0 | Flow based on approximately 30 cars/day at Philadelphia ratioed to total fleet by (492/275). Inspection costs accrued in paths 30 and 32. |
| 38 | 2 | Tighten anchor rods. | — | — | 3936 | $8.64 | Flow: each 6 months (492 cars x 4 units per car x 2 per year), (Budd)<br>Cost: 2 hours per car (Budd) |
| | 3 | Tighten dampers and check fluid level. | — | — | 1872 | $2.16 | Flow: approximately each 2 years (492 cars x 8 units per car x 0.5 per year), (Budd)<br>Cost: 1 hour per car (Budd) |

*CP # refers to truck component designation numbers (See Table 4.3a).

**Dashes indicate that quantity not used as an input data value or value given elsewhere in Table 4.3a or 4.3b.

***Flows computed from 492 x 12 cars/year x no. of components/ car. All unit costs for periodic inspection given on the basis of equivalent monthly inspections. Inspection times as estimated by Budd.

TABLE 4.3b (cont.)

AMCOACH INPUT DATA — ANNUAL MAINTENANCE COSTS AND FLOWS

| Computer Maintenance Path | CP #* | Description | Annual Component Flow** Number | Proportion Defective | Number Defective | Unit Path Cost | Data Source and Remarks (Labor at $17.27/hr.) |
|---|---|---|---|---|---|---|---|
| | 4 | Lubricate bearings | — | — | 1560 | $2.88 | Flow: approximately 30 months, AARCRB rule 26 (492 cars x 8 units per car x 0.4 per year) Cost: 10 min per bearing (Budd) |
| | 5 | Shim side frame | — | — | 8 | $25.90 | Flow: 8-10 per year (MAP) Cost: 3 hrs. per truck (Budd) |
| | 7 | Turn wheels | — | — | 3936 | $12.95 | Flow: Wheels turned each 120,000 miles*** (wheels turned 4 times, estimate) Cost: 3/4 hour per wheel (Budd) |
| | 9 | Add fluid in pneumatic system | — | — | 394 | $8.64 | Flow: Estimate once every 5 years (492 cars x 4 systems/car x 1/5 years), (Budd) Cost: 2 hours per car (1/2 hour per valve), (Budd) |
| | 11 | Clean air valve | — | — | 1968 | $17.27 | Flow: Once each 6 months (492 cars x 2 per car x 2 per year), (Budd) Cost: 2 hours per car (1 hour per valve), (Budd) |

*CP # refers to truck component designation numbers (See Table 4.3a).

**Dashes indicate that quantity not used as an input data value or value given elsewhere in Table 4.3a or 4.3b.

***Annual flow incorporates average car mileage of 120,000 miles/year.

TABLE 4.3b (cont.)

AMCOACH INPUT DATA — ANNUAL MAINTENANCE COSTS AND FLOWS

| Computer Maintenance Path | CP #* | Description | Annual Component Flow** Number | Annual Component Flow** Proportion Defective | Annual Component Flow** Number Defective | Unit Path Cost | Data Source and Remarks (Labor at $17.27/hr.) |
|---|---|---|---|---|---|---|---|
| | | Replace | | | | | |
| 39 | 2 | Air springs - coils | — | — | 394 | 276.32 | Flow: Replace each 5 years (replacement interval), (492 cars x 4 per car x 0.20 per year)<br>Cost: 16 hours per spring (Budd) |
| | 5 | Side bearing wear pad | — | — | 131 | 34.50 | Flow: Replace each 15 years (estimate), (492 x 4 per car x 1/15)<br>Cost: 2 hours per pad (estimate) |
| | 8 | Brake shoes (pairs)<br>Cylinders<br>Cables<br>Other brake components (hoses, keys, valves, heads, etc.) | — | — | 15744 | 37.30 | Flow: Replace each 30,000 miles*** (Budd), (8 per car)<br>Cost: (shoes): 2 hours per 8 pairs (Budd) = $4.32<br>(cylinders): 2 hours per cylinder, replace each 36 months (1 each 3 3 years, (requirement) = $11.51<br>(cables): 2 hours per cable, replace each 36 months (Budd) = $11.51<br>(other): 1.75 hours each set, replace each 36 months (MAP) = $9.96<br>Total Cost: $37.30 |
| | 10 | Speed sensors | — | — | 394 | 11.31 | Flow: Replace at rate of about 33 per month (MAP)<br>Cost: About 40 minutes (MAP) |

*CP # refers to truck component designation numbers (See Table 4.3a).

**Dashes indicate that quantity not used as an input data value or value given elsewhere in Table 4.3a or 4.3b.

***Annual flow incorporates average car mileage of 120,000 miles/year.

TABLE 4.3b (cont.)

AMCOACH INPUT DATA — ANNUAL MAINTENANCE COSTS AND FLOWS

| Computer Maintenance Path | CP #* | Description | Annual Component Flow** Number | Annual Component Flow** Proportion Defective | Annual Component Flow** Number Defective | Unit Path Cost | Data Source and Remarks (Labor at $17.27/hr.) |
|---|---|---|---|---|---|---|---|
| 42 | Wheelset Overhaul: 1, 4, 6, 7 | Replace journal rubbers<br>Rework bearings<br>Replace brake disks<br>Replace wheels | — | — | — | 51.81 | Cost: Cost to remove wheelset set and install an overhauled wheel set, 6 hours per wheelset = 51.81 per wheel (Budd) |

*CP # refers to truck component designation numbers (See Table 4.3a).

**Dashes indicate that quantity not used as an input data value or value given elsewhere in Table 4.3a or 4.3b.

TABLE 4.4

VALUES OF THE PARAMETERS C, D, E, AND K$ FOR THE AMCOACHES

| Node No. | Branch Node No. | Component No. | Identifiable Subassembly* | C** | D | E |
|---|---|---|---|---|---|---|
| 1 | 1 | All | K$ | 12.000 | | |
| 2 | 2 | All | K$ | 365.00 | | |
| 6 | 3 | 1 | K$ | | 1 | 0.090 |
| | | 2 | K$ | | 1 | 0.050 |
| | | 3 | K$ | | 1 | 0.085 |
| | | 4 | K$ | | 1 | 0.086 |
| | | 5 | K$ | | 1 | 0.092 |
| | | 6 | K$ | | 1 | 0.090 |
| | | 7 | K$ | | 1 | 0.070 |
| | | 8 | K$ | | 1 | 0.011 |
| | | 9 | K$ | | 1 | 0.090 |
| | | 10 | K$ | | 1 | 0.090 |
| | | 11 | K$ | | 1 | 0.054 |
| 7 | 4 | 1 | K$ | | 0.020 | 0.0082 |
| | | 2 | K$ | | 0.021 | 0.0077 |
| | | 3 | K$ | | 0.021 | 0.0082 |
| | | 4 | K$ | | 0.020 | 0.0082 |
| | | 5 | K$ | | 0.021 | 0.0083 |
| | | 6 | K$ | | 0.020 | 0.0082 |
| | | 7 | K$ | | 0.020 | 0.0080 |
| | | 8 | K$ | | 0.021 | 0.0072 |
| | | 9 | K$ | | 0.020 | 0.0082 |
| | | 10 | K$ | | 0.020 | 0.0082 |
| | | 11 | K$ | | 0.021 | 0.0077 |
| 10 | 5 | 1 | K$ | | 0.000 | 0.000 |
| | | 2 | | | 0.091 | 0.000 |
| | | 3 | | | 0.000 | 0.000 |
| | | 4 | K$ | | 0.000 | 0.000 |
| | | 5 | | | 0.936 | 0.000 |
| | | 6 | K$ | | 0.000 | 0.000 |
| | | 7 | K$ | | 0.117 | 0.002 |
| | | 8 | | | 1.000 | 1.000 |
| | | 9 | | | 0.000 | 0.000 |
| | | 10 | | | 1.000 | 1.000 |
| | | 11 | | | 0.000 | 0.000 |
| 11 | 6 | 1 | K$ | | 1.000 | 0.000 |
| | | 2 | | | 0.000 | 0.000 |
| | | 3 | | | 0.000 | 0.000 |
| | | 4 | K$ | | 1.000 | 0.000 |

*The component is part of an identifiable subassembly at this node if K$ parameter is used.

**Value of C for a component at a branch node is zero if a value is not given in the table for C, D, or E.

TABLE 4.4 (cont.)

VALUES OF THE PARAMETERS C, D, E, AND K$ FOR THE AMCOACHES

| Node No. | Branch Node No. | Component No. | Identifiable Subassembly | C | D | E |
|---|---|---|---|---|---|---|
| | 6 | 5 | | | 0.000 | 0.000 |
| | | 6 | K$ | | 1.000 | 1.000 |
| | | 7 | K$ | | 1.000 | 1.000 |
| | | 8 | | | 0.000 | 0.000 |
| | | 9 | | | 0.000 | 0.000 |
| | | 10 | | | 0.000 | 0.000 |
| | | 11 | | | 0.000 | 0.000 |
| 12 | 7 | 1 | | | 1.000 | 0.000 |
| | | 2 | | | 1.000 | 0.000 |
| | | 3 | | | 1.000 | 0.000 |
| | | 4 | | | 1.000 | 0.000 |
| | | 5 | | | 1.000 | 0.000 |
| | | 6 | | | 1.000 | 1.000 |
| | | 7 | | | 1.000 | 1.000 |
| | | 8 | | | 1.000 | 0.000 |
| | | 9 | | | 1.000 | 0.000 |
| | | 10 | | | 1.000 | 0.000 |
| | | 11 | | | 1.000 | 0.000 |
| 15 | 8 | 1 | K$ | | 1.000 | 0.000 |
| | | 2 | | | 1.000 | 0.000 |
| | | 3 | | | 1.000 | 0.000 |
| | | 4 | K$ | | 1.000 | 0.000 |
| | | 5 | | | 1.000 | 0.000 |
| | | 6 | K$ | | 1.000 | 1.000 |
| | | 7 | K$ | | 1.000 | 1.000 |
| | | 8 | | | 1.000 | 0.000 |
| | | 9 | | | 1.000 | 0.000 |
| | | 10 | | | 1.000 | 0.000 |
| | | 11 | | | 1.000 | 0.000 |

| Component Number | Population Size | Quality (Proportion Defective) |
|---|---|---|
| 1 | 3936 | 0.0041 |
| 2 | 1968 | 0.0458 |
| 3 | 3936 | 0.0099 |
| 4 | 3936 | 0.0083 |
| 5 | 1968 | 0.0014 |
| 6 | 3936 | 0.0041 |
| 7 | 3936 | 0.0250 |
| 8 | 3936 | 0.0833 |
| 9 | 1968 | 0.0041 |
| 10 | 1968 | 0.0041 |
| 11 | 984 | 0.0416 |

## 4.3 Base Case Analyses

This section gives the base case analyses which result for the Metroliner and Amcoach trucks from the data of Section 4.2. The base case analysis for the Metroliner is presented in Section 4.3.1. That for the Amcoaches is given in Section 4.3.2.

### 4.3.1 Base Case Analysis for the Metroliner

The base case analysis for the Metroliner is shown as Table 4.5a and 4.5b. Table 4.5a describes the maintenance operations which occur in the base case year. The table contains four columns. The first column gives the path numbers. The path numbers correspond to the uncircled numbers in the schematic diagram given as Figures 2.6-2.10. Each path can contain one, some, or all of the components -- those components that have a non-zero annual flow in a path are listed in Column 2 of the table. In Column 3 of the table, these annual flows are then given.* In Column 4 of the table, the quality of the flow for the component in the path is shown. This quality is the proportion (of the units for that component) which is defective. This quality is zero on path containing replacement units and is set to zero on paths where rework occurs.

Table 4.5b gives the costs for the base case analysis. As in Table 4.5a, the first two columns give the path number and component number. Only those paths and those components for which there are associated costs are given.

*It should be noted that path 1 represents the population for each component. Consequently, the number in Column 3 for path 1 is the population size for each component in the year represented by the base case. The numbers in Column 3 for the remaining paths are the annual flows of the components in that same year.

TABLE 4.5a

BASE CASE ANALYSIS FOR METROLINER --

FLOWS AND QUALITIES*

YEAR 0

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| PATH | 1 | COMPONENT | 1 | NUM | = | 488 | QUALITY | = | 0.0299 |
| PATH | 1 | COMPONENT | 2 | NUM | = | 488 | QUALITY | = | 0.0299 |
| PATH | 1 | COMPONENT | 3 | NUM | = | 488 | QUALITY | = | 0.0299 |
| PATH | 1 | COMPONENT | 4 | NUM | = | 488 | QUALITY | = | 0.0145 |
| PATH | 1 | COMPONENT | 5 | NUM | = | 122 | QUALITY | = | 0.0252 |
| PATH | 1 | COMPONENT | 6 | NUM | = | 244 | QUALITY | = | 0.0258 |
| PATH | 1 | COMPONENT | 7 | NUM | = | 488 | QUALITY | = | 0.3062 |
| PATH | 1 | COMPONENT | 8 | NUM | = | 488 | QUALITY | = | 0.1524 |
| PATH | 1 | COMPONENT | 9 | NUM | = | 122 | QUALITY | = | 0.0357 |
| PATH | 1 | COMPONENT | 10 | NUM | = | 122 | QUALITY | = | 0.0217 |
| PATH | 1 | COMPONENT | 11 | NUM | = | 122 | QUALITY | = | 0.0299 |
| PATH | 1 | COMPONENT | 12 | NUM | = | 244 | QUALITY | = | 0.0498 |
| PATH | 4 | COMPONENT | 3 | NUM/YR | = | 278 | QUALITY | = | 0.0000 |
| PATH | 4 | COMPONENT | 10 | NUM/YR | = | 67 | QUALITY | = | 0.0000 |
| PATH | 5 | COMPONENT | 2 | NUM/YR | = | 92 | QUALITY | = | 0.0000 |
| PATH | 5 | COMPONENT | 9 | NUM/YR | = | 39 | QUALITY | = | 0.0000 |
| PATH | 6 | COMPONENT | 1 | NUM/YR | = | 92 | QUALITY | = | 0.0000 |
| PATH | 7 | COMPONENT | 4 | NUM/YR | = | 181 | QUALITY | = | 0.0000 |
| PATH | 8 | COMPONENT | 7 | NUM/YR | = | 479 | QUALITY | = | 0.0000 |
| PATH | 9 | COMPONENT | 6 | NUM/YR | = | 50 | QUALITY | = | 0.0000 |
| PATH | 11 | COMPONENT | 8 | NUM/YR | = | 19589 | QUALITY | = | 0.0000 |
| PATH | 16 | COMPONENT | 3 | NUM/YR | = | 278 | QUALITY | = | 1.0000 |
| PATH | 16 | COMPONENT | 10 | NUM/YR | = | 67 | QUALITY | = | 0.9999 |
| PATH | 17 | COMPONENT | 2 | NUM/YR | = | 92 | QUALITY | = | 1.0000 |
| PATH | 17 | COMPONENT | 9 | NUM/YR | = | 39 | QUALITY | = | 0.9999 |
| PATH | 18 | COMPONENT | 1 | NUM/YR | = | 92 | QUALITY | = | 1.0000 |
| PATH | 19 | COMPONENT | 4 | NUM/YR | = | 181 | QUALITY | = | 1.0000 |
| PATH | 20 | COMPONENT | 7 | NUM/YR | = | 479 | QUALITY | = | 0.6831 |

*Paths and components listed are those for which non-zero flows occur.

TABLE 4.5a (cont.)

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| PATH | 21 | COMPONENT | 6 | NUM/YR | = | 50 | QUALITY = 0.9999 |
| PATH | 23 | COMPONENT | 8 | NUM/YR | = | 19589 | QUALITY = 1.0000 |
| PATH | 30 | COMPONENT | 1 | NUM/YR | = | 128490 | QUALITY = 0.0299 |
| PATH | 30 | COMPONENT | 2 | NUM/YR | = | 128490 | QUALITY = 0.0299 |
| PATH | 30 | COMPONENT | 3 | NUM/YR | = | 128490 | QUALITY = 0.0299 |
| PATH | 30 | COMPONENT | 4 | NUM/YR | = | 128490 | QUALITY = 0.0145 |
| PATH | 30 | COMPONENT | 5 | NUM/YR | = | 32122 | QUALITY = 0.0252 |
| PATH | 30 | COMPONENT | 6 | NUM/YR | = | 64245 | QUALITY = 0.0258 |
| PATH | 30 | COMPONENT | 7 | NUM/YR | = | 128490 | QUALITY = 0.3062 |
| PATH | 30 | COMPONENT | 8 | NUM/YR | = | 128490 | QUALITY = 0.1524 |
| PATH | 30 | COMPONENT | 9 | NUM/YR | = | 32122 | QUALITY = 0.0357 |
| PATH | 30 | COMPONENT | 10 | NUM/YR | = | 32122 | QUALITY = 0.0217 |
| PATH | 30 | COMPONENT | 11 | NUM/YR | = | 32122 | QUALITY = 0.0299 |
| PATH | 30 | COMPONENT | 12 | NUM/YR | = | 64245 | QUALITY = 0.0498 |
| PATH | 31 | COMPONENT | 1 | NUM/YR | = | 124201 | QUALITY = 0.0286 |
| PATH | 31 | COMPONENT | 2 | NUM/YR | = | 124201 | QUALITY = 0.0286 |
| PATH | 31 | COMPONENT | 3 | NUM/YR | = | 124201 | QUALITY = 0.0286 |
| PATH | 31 | COMPONENT | 4 | NUM/YR | = | 124201 | QUALITY = 0.0138 |
| PATH | 31 | COMPONENT | 5 | NUM/YR | = | 31050 | QUALITY = 0.0241 |
| PATH | 31 | COMPONENT | 6 | NUM/YR | = | 62100 | QUALITY = 0.0246 |
| PATH | 31 | COMPONENT | 7 | NUM/YR | = | 124201 | QUALITY = 0.2965 |
| PATH | 31 | COMPONENT | 8 | NUM/YR | = | 124201 | QUALITY = 0.1466 |
| PATH | 31 | COMPONENT | 9 | NUM/YR | = | 31050 | QUALITY = 0.0341 |
| PATH | 31 | COMPONENT | 10 | NUM/YR | = | 31050 | QUALITY = 0.0208 |
| PATH | 31 | COMPONENT | 11 | NUM/YR | = | 31050 | QUALITY = 0.0286 |
| PATH | 31 | COMPONENT | 12 | NUM/YR | = | 62100 | QUALITY = 0.0477 |
| PATH | 32 | COMPONENT | 1 | NUM/YR | = | 5856 | QUALITY = 0.0299 |
| PATH | 32 | COMPONENT | 2 | NUM/YR | = | 5856 | QUALITY = 0.0299 |
| PATH | 32 | COMPONENT | 3 | NUM/YR | = | 5856 | QUALITY = 0.0299 |
| PATH | 32 | COMPONENT | 4 | NUM/YR | = | 5856 | QUALITY = 0.0145 |
| PATH | 32 | COMPONENT | 5 | NUM/YR | = | 1464 | QUALITY = 0.0252 |
| PATH | 32 | COMPONENT | 6 | NUM/YR | = | 2928 | QUALITY = 0.0258 |
| PATH | 32 | COMPONENT | 7 | NUM/YR | = | 5856 | QUALITY = 0.3062 |
| PATH | 32 | COMPONENT | 8 | NUM/YR | = | 5856 | QUALITY = 0.1524 |
| PATH | 32 | COMPONENT | 9 | NUM/YR | = | 1464 | QUALITY = 0.0357 |
| PATH | 32 | COMPONENT | 10 | NUM/YR | = | 1464 | QUALITY = 0.0217 |
| PATH | 32 | COMPONENT | 11 | NUM/YR | = | 1464 | QUALITY = 0.0299 |
| PATH | 32 | COMPONENT | 12 | NUM/YR | = | 2928 | QUALITY = 0.0498 |

TABLE 4.5a (cont.)

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| PATH | 33 | COMPONENT | 1 | NUM/YR | = | 3164 | QUALITY | = | 0.0299 |
| PATH | 33 | COMPONENT | 2 | NUM/YR | = | 3164 | QUALITY | = | 0.0299 |
| PATH | 33 | COMPONENT | 3 | NUM/YR | = | 3164 | QUALITY | = | 0.0299 |
| PATH | 33 | COMPONENT | 4 | NUM/YR | = | 3164 | QUALITY | = | 0.0145 |
| PATH | 33 | COMPONENT | 5 | NUM/YR | = | 791 | QUALITY | = | 0.0252 |
| PATH | 33 | COMPONENT | 6 | NUM/YR | = | 1582 | QUALITY | = | 0.0258 |
| PATH | 33 | COMPONENT | 7 | NUM/YR | = | 3164 | QUALITY | = | 0.3062 |
| PATH | 33 | COMPONENT | 8 | NUM/YR | = | 3164 | QUALITY | = | 0.1524 |
| PATH | 33 | COMPONENT | 9 | NUM/YR | = | 791 | QUALITY | = | 0.0357 |
| PATH | 33 | COMPONENT | 10 | NUM/YR | = | 791 | QUALITY | = | 0.0217 |
| PATH | 33 | COMPONENT | 11 | NUM/YR | = | 791 | QUALITY | = | 0.0299 |
| PATH | 33 | COMPONENT | 12 | NUM/YR | = | 1582 | QUALITY | = | 0.0498 |
| PATH | 34 | COMPONENT | 1 | NUM/YR | = | 2691 | QUALITY | = | 0.0299 |
| PATH | 34 | COMPONENT | 2 | NUM/YR | = | 2691 | QUALITY | = | 0.0299 |
| PATH | 34 | COMPONENT | 3 | NUM/YR | = | 2691 | QUALITY | = | 0.0299 |
| PATH | 34 | COMPONENT | 4 | NUM/YR | = | 2691 | QUALITY | = | 0.0145 |
| PATH | 34 | COMPONENT | 5 | NUM/YR | = | 672 | QUALITY | = | 0.0252 |
| PATH | 34 | COMPONENT | 6 | NUM/YR | = | 1345 | QUALITY | = | 0.0258 |
| PATH | 34 | COMPONENT | 7 | NUM/YR | = | 2691 | QUALITY | = | 0.3062 |
| PATH | 34 | COMPONENT | 8 | NUM/YR | = | 2691 | QUALITY | = | 0.1524 |
| PATH | 34 | COMPONENT | 9 | NUM/YR | = | 672 | QUALITY | = | 0.0357 |
| PATH | 34 | COMPONENT | 10 | NUM/YR | = | 672 | QUALITY | = | 0.0217 |
| PATH | 34 | COMPONENT | 11 | NUM/YR | = | 672 | QUALITY | = | 0.0299 |
| PATH | 34 | COMPONENT | 12 | NUM/YR | = | 1345 | QUALITY | = | 0.0498 |
| PATH | 35 | COMPONENT | 1 | NUM/YR | = | 4289 | QUALITY | = | 0.0678 |
| PATH | 35 | COMPONENT | 2 | NUM/YR | = | 4289 | QUALITY | = | 0.0678 |
| PATH | 35 | COMPONENT | 3 | NUM/YR | = | 4289 | QUALITY | = | 0.0678 |
| PATH | 35 | COMPONENT | 4 | NUM/YR | = | 4289 | QUALITY | = | 0.0332 |
| PATH | 35 | COMPONENT | 5 | NUM/YR | = | 1072 | QUALITY | = | 0.0574 |
| PATH | 35 | COMPONENT | 6 | NUM/YR | = | 2144 | QUALITY | = | 0.0585 |
| PATH | 35 | COMPONENT | 7 | NUM/YR | = | 4289 | QUALITY | = | 0.5870 |
| PATH | 35 | COMPONENT | 8 | NUM/YR | = | 4289 | QUALITY | = | 0.3220 |
| PATH | 35 | COMPONENT | 9 | NUM/YR | = | 1072 | QUALITY | = | 0.0806 |
| PATH | 35 | COMPONENT | 10 | NUM/YR | = | 1072 | QUALITY | = | 0.0495 |
| PATH | 35 | COMPONENT | 11 | NUM/YR | = | 1072 | QUALITY | = | 0.0678 |
| PATH | 35 | COMPONENT | 12 | NUM/YR | = | 2144 | QUALITY | = | 0.1118 |
| PATH | 36 | COMPONENT | 1 | NUM/YR | = | 6980 | QUALITY | = | 0.0532 |
| PATH | 36 | COMPONENT | 2 | NUM/YR | = | 6980 | QUALITY | = | 0.0532 |
| PATH | 36 | COMPONENT | 3 | NUM/YR | = | 6980 | QUALITY | = | 0.0532 |
| PATH | 36 | COMPONENT | 4 | NUM/YR | = | 6980 | QUALITY | = | 0.0260 |
| PATH | 36 | COMPONENT | 5 | NUM/YR | = | 1745 | QUALITY | = | 0.0450 |

TABLE 4.5a (cont.)

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| PATH | 36 | COMPONENT | 6 | NUM/YR | = | 3490 | QUALITY | = | 0.0459 |
| PATH | 36 | COMPONENT | 7 | NUM/YR | = | 6980 | QUALITY | = | 0.4787 |
| PATH | 36 | COMPONENT | 8 | NUM/YR | = | 6980 | QUALITY | = | 0.2566 |
| PATH | 36 | COMPONENT | 9 | NUM/YR | = | 1745 | QUALITY | = | 0.0633 |
| PATH | 36 | COMPONENT | 10 | NUM/YR | = | 1745 | QUALITY | = | 0.0388 |
| PATH | 36 | COMPONENT | 11 | NUM/YR | = | 1745 | QUALITY | = | 0.0532 |
| PATH | 36 | COMPONENT | 12 | NUM/YR | = | 3490 | QUALITY | = | 0.0879 |
| PATH | 37 | COMPONENT | 1 | NUM/YR | = | 6980 | QUALITY | = | 0.0532 |
| PATH | 37 | COMPONENT | 2 | NUM/YR | = | 6980 | QUALITY | = | 0.0532 |
| PATH | 37 | COMPONENT | 3 | NUM/YR | = | 6980 | QUALITY | = | 0.0532 |
| PATH | 37 | COMPONENT | 4 | NUM/YR | = | 6980 | QUALITY | = | 0.0260 |
| PATH | 37 | COMPONENT | 5 | NUM/YR | = | 1745 | QUALITY | = | 0.0450 |
| PATH | 37 | COMPONENT | 6 | NUM/YR | = | 3490 | QUALITY | = | 0.0459 |
| PATH | 37 | COMPONENT | 7 | NUM/YR | = | 6980 | QUALITY | = | 0.4787 |
| PATH | 37 | COMPONENT | 8 | NUM/YR | = | 6980 | QUALITY | = | 0.2566 |
| PATH | 37 | COMPONENT | 9 | NUM/YR | = | 1745 | QUALITY | = | 0.0633 |
| PATH | 37 | COMPONENT | 10 | NUM/YR | = | 1745 | QUALITY | = | 0.0388 |
| PATH | 37 | COMPONENT | 11 | NUM/YR | = | 1745 | QUALITY | = | 0.0532 |
| PATH | 37 | COMPONENT | 12 | NUM/YR | = | 3490 | QUALITY | = | 0.0879 |
| PATH | 39 | COMPONENT | 3 | NUM/YR | = | 6980 | QUALITY | = | 0.0532 |
| PATH | 39 | COMPONENT | 9 | NUM/YR | = | 1706 | QUALITY | = | 0.0418 |
| PATH | 39 | COMPONENT | 10 | NUM/YR | = | 1745 | QUALITY | = | 0.0388 |
| PATH | 40 | COMPONENT | 3 | NUM/YR | = | 6702 | QUALITY | = | 0.0000 |
| PATH | 40 | COMPONENT | 9 | NUM/YR | = | 1706 | QUALITY | = | 0.0000 |
| PATH | 40 | COMPONENT | 10 | NUM/YR | = | 1677 | QUALITY | = | 0.0000 |
| PATH | 41 | COMPONENT | 3 | NUM/YR | = | 6980 | QUALITY | = | 0.0000 |
| PATH | 41 | COMPONENT | 9 | NUM/YR | = | 1706 | QUALITY | = | 0.0000 |

TABLE 4.5a (cont.)

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| PATH | 41 | COMPONENT | 10 | NUM/YR | = | 1745 | QUALITY | = | 0.0000 |
| PATH | 42 | COMPONENT | 1 | NUM/YR | = | 6980 | QUALITY | = | 0.0532 |
| PATH | 42 | COMPONENT | 2 | NUM/YR | = | 6980 | QUALITY | = | 0.0532 |
| PATH | 42 | COMPONENT | 4 | NUM/YR | = | 6980 | QUALITY | = | 0.0260 |
| PATH | 42 | COMPONENT | 5 | NUM/YR | = | 1745 | QUALITY | = | 0.0450 |
| PATH | 42 | COMPONENT | 6 | NUM/YR | = | 3490 | QUALITY | = | 0.0459 |
| PATH | 42 | COMPONENT | 7 | NUM/YR | = | 6980 | QUALITY | = | 0.4787 |
| PATH | 42 | COMPONENT | 8 | NUM/YR | = | 6980 | QUALITY | = | 0.2566 |
| PATH | 42 | COMPONENT | 9 | NUM/YR | = | 39 | QUALITY | = | 0.9999 |
| PATH | 42 | COMPONENT | 11 | NUM/YR | = | 1745 | QUALITY | = | 0.0532 |
| PATH | 42 | COMPONENT | 12 | NUM/YR | = | 3490 | QUALITY | = | 0.0879 |
| PATH | 43 | COMPONENT | 2 | NUM/YR | = | 6980 | QUALITY | = | 0.0532 |
| PATH | 43 | COMPONENT | 8 | NUM/YR | = | 6980 | QUALITY | = | 0.2566 |
| PATH | 43 | COMPONENT | 9 | NUM/YR | = | 39 | QUALITY | = | 0.9999 |
| PATH | 43 | COMPONENT | 11 | NUM/YR | = | 1745 | QUALITY | = | 0.0532 |
| PATH | 44 | COMPONENT | 2 | NUM/YR | = | 6887 | QUALITY | = | 0.0000 |
| PATH | 44 | COMPONENT | 8 | NUM/YR | = | 6980 | QUALITY | = | 0.2566 |
| PATH | 44 | COMPONENT | 11 | NUM/YR | = | 1745 | QUALITY | = | 0.0000 |
| PATH | 45 | COMPONENT | 2 | NUM/YR | = | 6980 | QUALITY | = | 0.0000 |
| PATH | 45 | COMPONENT | 8 | NUM/YR | = | 6980 | QUALITY | = | 0.2566 |
| PATH | 45 | COMPONENT | 9 | NUM/YR | = | 39 | QUALITY | = | 0.0000 |
| PATH | 45 | COMPONENT | 11 | NUM/YR | = | 1745 | QUALITY | = | 0.0000 |
| PATH | 46 | COMPONENT | 1 | NUM/YR | = | 6980 | QUALITY | = | 0.0532 |
| PATH | 46 | COMPONENT | 4 | NUM/YR | = | 6980 | QUALITY | = | 0.0260 |
| PATH | 46 | COMPONENT | 5 | NUM/YR | = | 1745 | QUALITY | = | 0.0450 |
| PATH | 46 | COMPONENT | 6 | NUM/YR | = | 3490 | QUALITY | = | 0.0459 |
| PATH | 46 | COMPONENT | 7 | NUM/YR | = | 6980 | QUALITY | = | 0.4787 |
| PATH | 46 | COMPONENT | 12 | NUM/YR | = | 3490 | QUALITY | = | 0.0879 |
| PATH | 48 | COMPONENT | 1 | NUM/YR | = | 6980 | QUALITY | = | 0.0532 |
| PATH | 48 | COMPONENT | 4 | NUM/YR | = | 6980 | QUALITY | = | 0.0260 |
| PATH | 48 | COMPONENT | 5 | NUM/YR | = | 1745 | QUALITY | = | 0.0450 |

TABLE 4.5a (cont.)

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| PATH | 48 | COMPONENT | 6 | NUM/YR | = | 3490 | QUALITY | = | 0.0459 |
| PATH | 48 | COMPONENT | 7 | NUM/YR | = | 6980 | QUALITY | = | 0.4787 |
| PATH | 48 | COMPONENT | 12 | NUM/YR | = | 3183 | QUALITY | = | 0.0000 |
| PATH | 49 | COMPONENT | 4 | NUM/YR | = | 4860 | QUALITY | = | 0.0373 |
| PATH | 49 | COMPONENT | 6 | NUM/YR | = | 2430 | QUALITY | = | 0.0502 |
| PATH | 49 | COMPONENT | 7 | NUM/YR | = | 4860 | QUALITY | = | 0.6831 |
| PATH | 50 | COMPONENT | 1 | NUM/YR | = | 6980 | QUALITY | = | 0.0532 |
| PATH | 50 | COMPONENT | 4 | NUM/YR | = | 2119 | QUALITY | = | 0.0000 |
| PATH | 50 | COMPONENT | 5 | NUM/YR | = | 1745 | QUALITY | = | 0.0450 |
| PATH | 50 | COMPONENT | 6 | NUM/YR | = | 1059 | QUALITY | = | 0.0360 |
| PATH | 50 | COMPONENT | 7 | NUM/YR | = | 2119 | QUALITY | = | 0.0100 |
| PATH | 50 | COMPONENT | 12 | NUM/YR | = | 3183 | QUALITY | = | 0.0000 |
| PATH | 51 | COMPONENT | 1 | NUM/YR | = | 6887 | QUALITY | = | 0.0000 |
| PATH | 51 | COMPONENT | 4 | NUM/YR | = | 2119 | QUALITY | = | 0.0000 |
| PATH | 51 | COMPONENT | 5 | NUM/YR | = | 1745 | QUALITY | = | 0.0000 |
| PATH | 51 | COMPONENT | 6 | NUM/YR | = | 1059 | QUALITY | = | 0.0360 |
| PATH | 51 | COMPONENT | 7 | NUM/YR | = | 2119 | QUALITY | = | 0.0100 |
| PATH | 51 | COMPONENT | 12 | NUM/YR | = | 3183 | QUALITY | = | 0.0000 |
| PATH | 52 | COMPONENT | 1 | NUM/YR | = | 6980 | QUALITY | = | 0.0000 |
| PATH | 52 | COMPONENT | 4 | NUM/YR | = | 2119 | QUALITY | = | 0.0000 |
| PATH | 52 | COMPONENT | 5 | NUM/YR | = | 1745 | QUALITY | = | 0.0000 |
| PATH | 52 | COMPONENT | 6 | NUM/YR | = | 1059 | QUALITY | = | 0.0360 |
| PATH | 52 | COMPONENT | 7 | NUM/YR | = | 2119 | QUALITY | = | 0.0100 |
| PATH | 52 | COMPONENT | 12 | NUM/YR | = | 3183 | QUALITY | = | 0.0000 |
| PATH | 53 | COMPONENT | 4 | NUM/YR | = | 4860 | QUALITY | = | 0.0000 |
| PATH | 53 | COMPONENT | 6 | NUM/YR | = | 2430 | QUALITY | = | 0.0000 |
| PATH | 53 | COMPONENT | 7 | NUM/YR | = | 4860 | QUALITY | = | 0.0000 |
| PATH | 54 | COMPONENT | 1 | NUM/YR | = | 6980 | QUALITY | = | 0.0000 |
| PATH | 54 | COMPONENT | 4 | NUM/YR | = | 6980 | QUALITY | = | 0.0000 |
| PATH | 54 | COMPONENT | 5 | NUM/YR | = | 1745 | QUALITY | = | 0.0000 |
| PATH | 54 | COMPONENT | 6 | NUM/YR | = | 3490 | QUALITY | = | 0.0109 |
| PATH | 54 | COMPONENT | 7 | NUM/YR | = | 6980 | QUALITY | = | 0.0030 |
| PATH | 54 | COMPONENT | 12 | NUM/YR | = | 3183 | QUALITY | = | 0.0000 |

TABLE 4.5a (cont.)

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| PATH | 55 | COMPONENT | 12 | NUM/YR | = | 306 | QUALITY = | 0.0000 |
| PATH | 56 | COMPONENT | 1 | NUM/YR | = | 6980 | QUALITY = | 0.0000 |
| PATH | 56 | COMPONENT | 4 | NUM/YR | = | 6980 | QUALITY = | 0.0000 |
| PATH | 56 | COMPONENT | 5 | NUM/YR | = | 1745 | QUALITY = | 0.0000 |
| PATH | 56 | COMPONENT | 6 | NUM/YR | = | 3490 | QUALITY = | 0.0109 |
| PATH | 56 | COMPONENT | 7 | NUM/YR | = | 6980 | QUALITY = | 0.0030 |
| PATH | 56 | COMPONENT | 12 | NUM/YR | = | 3490 | QUALITY = | 0.0000 |
| PATH | 57 | COMPONENT | 1 | NUM/YR | = | 6980 | QUALITY = | 0.0000 |
| PATH | 57 | COMPONENT | 2 | NUM/YR | = | 6980 | QUALITY = | 0.0000 |
| PATH | 57 | COMPONENT | 4 | NUM/YR | = | 6980 | QUALITY = | 0.0000 |
| PATH | 57 | COMPONENT | 5 | NUM/YR | = | 1745 | QUALITY = | 0.0000 |
| PATH | 57 | COMPONENT | 6 | NUM/YR | = | 3490 | QUALITY = | 0.0109 |
| PATH | 57 | COMPONENT | 7 | NUM/YR | = | 6980 | QUALITY = | 0.0030 |
| PATH | 57 | COMPONENT | 8 | NUM/YR | = | 6980 | QUALITY = | 0.2566 |
| PATH | 57 | COMPONENT | 9 | NUM/YR | = | 39 | QUALITY = | 0.0000 |
| PATH | 57 | COMPONENT | 11 | NUM/YR | = | 1745 | QUALITY = | 0.0000 |
| PATH | 57 | COMPONENT | 12 | NUM/YR | = | 3490 | QUALITY = | 0.0000 |
| PATH | 58 | COMPONENT | 1 | NUM/YR | = | 6980 | QUALITY = | 0.0000 |
| PATH | 58 | COMPONENT | 2 | NUM/YR | = | 6980 | QUALITY = | 0.0000 |
| PATH | 58 | COMPONENT | 3 | NUM/YR | = | 6980 | QUALITY = | 0.0000 |
| PATH | 58 | COMPONENT | 4 | NUM/YR | = | 6980 | QUALITY = | 0.0000 |
| PATH | 58 | COMPONENT | 5 | NUM/YR | = | 1745 | QUALITY = | 0.0000 |
| PATH | 58 | COMPONENT | 6 | NUM/YR | = | 3490 | QUALITY = | 0.0109 |
| PATH | 58 | COMPONENT | 7 | NUM/YR | = | 6980 | QUALITY = | 0.0030 |
| PATH | 58 | COMPONENT | 8 | NUM/YR | = | 6980 | QUALITY = | 0.2566 |
| PATH | 58 | COMPONENT | 9 | NUM/YR | = | 1745 | QUALITY = | 0.0000 |
| PATH | 58 | COMPONENT | 10 | NUM/YR | = | 1745 | QUALITY = | 0.0000 |
| PATH | 58 | COMPONENT | 11 | NUM/YR | = | 1745 | QUALITY = | 0.0000 |
| PATH | 58 | COMPONENT | 12 | NUM/YR | = | 3490 | QUALITY = | 0.0000 |
| PATH | 59 | COMPONENT | 1 | NUM/YR | = | 6980 | QUALITY = | 0.0000 |
| PATH | 59 | COMPONENT | 2 | NUM/YR | = | 6980 | QUALITY = | 0.0000 |
| PATH | 59 | COMPONENT | 3 | NUM/YR | = | 6980 | QUALITY = | 0.0000 |
| PATH | 59 | COMPONENT | 4 | NUM/YR | = | 6980 | QUALITY = | 0.0000 |
| PATH | 59 | COMPONENT | 5 | NUM/YR | = | 1745 | QUALITY = | 0.0000 |
| PATH | 59 | COMPONENT | 6 | NUM/YR | = | 3490 | QUALITY = | 0.0109 |
| PATH | 59 | COMPONENT | 7 | NUM/YR | = | 6980 | QUALITY = | 0.0030 |
| PATH | 59 | COMPONENT | 8 | NUM/YR | = | 6980 | QUALITY = | 0.2566 |
| PATH | 59 | COMPONENT | 9 | NUM/YR | = | 1745 | QUALITY = | 0.0000 |
| PATH | 59 | COMPONENT | 10 | NUM/YR | = | 1745 | QUALITY = | 0.0000 |
| PATH | 59 | COMPONENT | 11 | NUM/YR | = | 1745 | QUALITY = | 0.0000 |
| PATH | 59 | COMPONENT | 12 | NUM/YR | = | 3490 | QUALITY = | 0.0000 |

TABLE 4.5a (cont.)

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| PATH | 60 | COMPONENT | 1 | NUM/YR | = | 6980 | QUALITY | = | 0.0000 |
| PATH | 60 | COMPONENT | 2 | NUM/YR | = | 6980 | QUALITY | = | 0.0000 |
| PATH | 60 | COMPONENT | 3 | NUM/YR | = | 6980 | QUALITY | = | 0.0000 |
| PATH | 60 | COMPONENT | 4 | NUM/YR | = | 6980 | QUALITY | = | 0.0000 |
| PATH | 60 | COMPONENT | 5 | NUM/YR | = | 1745 | QUALITY | = | 0.0000 |
| PATH | 60 | COMPONENT | 6 | NUM/YR | = | 3490 | QUALITY | = | 0.0109 |
| PATH | 60 | COMPONENT | 7 | NUM/YR | = | 6980 | QUALITY | = | 0.0030 |
| PATH | 60 | COMPONENT | 8 | NUM/YR | = | 6980 | QUALITY | = | 0.2566 |
| PATH | 60 | COMPONENT | 9 | NUM/YR | = | 1745 | QUALITY | = | 0.0000 |
| PATH | 60 | COMPONENT | 10 | NUM/YR | = | 1745 | QUALITY | = | 0.0000 |
| PATH | 60 | COMPONENT | 11 | NUM/YR | = | 1745 | QUALITY | = | 0.0000 |
| PATH | 60 | COMPONENT | 12 | NUM/YR | = | 3490 | QUALITY | = | 0.0000 |
| PATH | 61 | COMPONENT | 4 | NUM/YR | = | 4380 | QUALITY | = | 0.0000 |
| PATH | 61 | COMPONENT | 6 | NUM/YR | = | 2190 | QUALITY | = | 0.0000 |
| PATH | 61 | COMPONENT | 7 | NUM/YR | = | 4380 | QUALITY | = | 0.0000 |
| PATH | 62 | COMPONENT | 4 | NUM/YR | = | 479 | QUALITY | = | 0.3782 |
| PATH | 62 | COMPONENT | 6 | NUM/YR | = | 239 | QUALITY | = | 0.5091 |
| PATH | 62 | COMPONENT | 7 | NUM/YR | = | 479 | QUALITY | = | 0.6831 |
| PATH | 63 | COMPONENT | 4 | NUM/YR | = | 479 | QUALITY | = | 0.3782 |
| PATH | 64 | COMPONENT | 4 | NUM/YR | = | 298 | QUALITY | = | 0.0000 |
| PATH | 65 | COMPONENT | 4 | NUM/YR | = | 479 | QUALITY | = | 0.0000 |
| PATH | 66 | COMPONENT | 6 | NUM/YR | = | 239 | QUALITY | = | 0.5091 |
| PATH | 66 | COMPONENT | 7 | NUM/YR | = | 479 | QUALITY | = | 0.6831 |
| PATH | 67 | COMPONENT | 6 | NUM/YR | = | 117 | QUALITY | = | 0.0000 |
| PATH | 67 | COMPONENT | 7 | NUM/YR | = | 479 | QUALITY | = | 0.6831 |
| PATH | 68 | COMPONENT | 6 | NUM/YR | = | 117 | QUALITY | = | 0.0000 |
| PATH | 69 | COMPONENT | 6 | NUM/YR | = | 117 | QUALITY | = | 0.0000 |
| PATH | 69 | COMPONENT | 7 | NUM/YR | = | 479 | QUALITY | = | 0.0000 |
| PATH | 70 | COMPONENT | 6 | NUM/YR | = | 122 | QUALITY | = | 0.9999 |
| PATH | 71 | COMPONENT | 6 | NUM/YR | = | 72 | QUALITY | = | 0.0000 |
| PATH | 72 | COMPONENT | 6 | NUM/YR | = | 122 | QUALITY | = | 0.0000 |

TABLE 4.5a (cont.)

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| PATH | 73 | COMPONENT | 6 | NUM/YR | = | 239 | QUALITY = | 0.0000 |
| PATH | 73 | COMPONENT | 7 | NUM/YR | = | 479 | QUALITY = | 0.0000 |
| PATH | 74 | COMPONENT | 4 | NUM/YR | = | 479 | QUALITY = | 0.0000 |
| PATH | 74 | COMPONENT | 6 | NUM/YR | = | 239 | QUALITY = | 0.0000 |
| PATH | 74 | COMPONENT | 7 | NUM/YR | = | 479 | QUALITY = | 0.0000 |
| PATH | 76 | COMPONENT | 12 | NUM/YR | = | 76 | QUALITY = | 0.9999 |
| PATH | 77 | COMPONENT | 12 | NUM/YR | = | 76 | QUALITY = | 0.0000 |
| PATH | 78 | COMPONENT | 12 | NUM/YR | = | 76 | QUALITY = | 0.0000 |
| PATH | 79 | COMPONENT | 1 | NUM/YR | = | 128490 | QUALITY = | 0.0299 |
| PATH | 79 | COMPONENT | 2 | NUM/YR | = | 128490 | QUALITY = | 0.0299 |
| PATH | 79 | COMPONENT | 3 | NUM/YR | = | 128490 | QUALITY = | 0.0299 |
| PATH | 79 | COMPONENT | 4 | NUM/YR | = | 128490 | QUALITY = | 0.0145 |
| PATH | 79 | COMPONENT | 5 | NUM/YR | = | 32122 | QUALITY = | 0.0252 |
| PATH | 79 | COMPONENT | 6 | NUM/YR | = | 64245 | QUALITY = | 0.0258 |
| PATH | 79 | COMPONENT | 7 | NUM/YR | = | 128490 | QUALITY = | 0.3062 |
| PATH | 79 | COMPONENT | 8 | NUM/YR | = | 128490 | QUALITY = | 0.1524 |
| PATH | 79 | COMPONENT | 9 | NUM/YR | = | 32122 | QUALITY = | 0.0357 |
| PATH | 79 | COMPONENT | 10 | NUM/YR | = | 32122 | QUALITY = | 0.0217 |
| PATH | 79 | COMPONENT | 11 | NUM/YR | = | 32122 | QUALITY = | 0.0299 |
| PATH | 79 | COMPONENT | 12 | NUM/YR | = | 64245 | QUALITY = | 0.0498 |
| PATH | 80 | COMPONENT | 1 | NUM/YR | = | 128490 | QUALITY = | 0.0299 |
| PATH | 80 | COMPONENT | 2 | NUM/YR | = | 128490 | QUALITY = | 0.0299 |
| PATH | 80 | COMPONENT | 3 | NUM/YR | = | 128490 | QUALITY = | 0.0299 |
| PATH | 80 | COMPONENT | 4 | NUM/YR | = | 128490 | QUALITY = | 0.0145 |
| PATH | 80 | COMPONENT | 5 | NUM/YR | = | 32122 | QUALITY = | 0.0252 |
| PATH | 80 | COMPONENT | 6 | NUM/YR | = | 64245 | QUALITY = | 0.0258 |
| PATH | 80 | COMPONENT | 7 | NUM/YR | = | 128490 | QUALITY = | 0.3062 |
| PATH | 80 | COMPONENT | 8 | NUM/YR | = | 108900 | QUALITY = | 0.0000 |
| PATH | 80 | COMPONENT | 9 | NUM/YR | = | 32122 | QUALITY = | 0.0357 |
| PATH | 80 | COMPONENT | 10 | NUM/YR | = | 32122 | QUALITY = | 0.0217 |
| PATH | 80 | COMPONENT | 11 | NUM/YR | = | 32122 | QUALITY = | 0.0299 |

TABLE 4.5a (cont.)

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| PATH | 80 | COMPONENT | 12 | NUM/YR | = | 64245 | QUALITY | = | 0.0498 |
| PATH | 81 | COMPONENT | 1 | NUM/YR | = | 128490 | QUALITY | = | 0.0299 |
| PATH | 81 | COMPONENT | 2 | NUM/YR | = | 128490 | QUALITY | = | 0.0299 |
| PATH | 81 | COMPONENT | 3 | NUM/YR | = | 128490 | QUALITY | = | 0.0299 |
| PATH | 81 | COMPONENT | 4 | NUM/YR | = | 128490 | QUALITY | = | 0.0145 |
| PATH | 81 | COMPONENT | 5 | NUM/YR | = | 32122 | QUALITY | = | 0.0252 |
| PATH | 81 | COMPONENT | 6 | NUM/YR | = | 64245 | QUALITY | = | 0.0258 |
| PATH | 81 | COMPONENT | 7 | NUM/YR | = | 128490 | QUALITY | = | 0.3062 |
| PATH | 81 | COMPONENT | 8 | NUM/YR | = | 128490 | QUALITY | = | 0.0000 |
| PATH | 81 | COMPONENT | 9 | NUM/YR | = | 32122 | QUALITY | = | 0.0357 |
| PATH | 81 | COMPONENT | 10 | NUM/YR | = | 32122 | QUALITY | = | 0.0217 |
| PATH | 81 | COMPONENT | 11 | NUM/YR | = | 32122 | QUALITY | = | 0.0299 |
| PATH | 81 | COMPONENT | 12 | NUM/YR | = | 64245 | QUALITY | = | 0.0498 |

TABLE 4.5b

BASE CASE ANALYSIS FOR METROLINER — COSTS*

| | | | | | | |
|---|---|---|---|---|---|---|
| PATH | 4; | COMPONENT | 3; | PATH COST | = | $13928.95 |
| PATH | 4; | COMPONENT | 10; | PATH COST | = | $3387.28 |
| PATH | 5; | COMPONENT | 2; | PATH COST | = | $13928.95 |
| PATH | 5; | COMPONENT | 9; | PATH COST | = | $9786.03 |
| PATH | 6; | COMPONENT | 1; | PATH COST | = | $18571.93 |
| PATH | 7; | COMPONENT | 4; | PATH COST | = | $27227.78 |
| PATH | 8; | COMPONENT | 7; | PATH COST | = | $95971.07 |
| PATH | 9; | COMPONENT | 6; | PATH COST | = | $125158.83 |
| PATH | 16; | COMPONENT | 3; | PATH COST | = | $-278.57 |
| PATH | 17; | COMPONENT | 2; | PATH COST | = | $-92.85 |
| PATH | 18; | COMPONENT | 1; | PATH COST | = | $-92.85 |
| PATH | 19; | COMPONENT | 4; | PATH COST | = | $-1089.11 |
| PATH | 20; | COMPONENT | 7; | PATH COST | = | $-9597.10 |
| PATH | 21; | COMPONENT | 6; | PATH COST | = | $-1251.58 |
| PATH | 23; | COMPONENT | 8; | PATH COST | = | $156716.14 |
| PATH | 30; | COMPONENT | 1; | PATH COST | = | $25000.00 |
| PATH | 32; | COMPONENT | 1; | PATH COST | = | $25000.00 |
| PATH | 36; | COMPONENT | 1; | PATH COST | = | $10052.17 |
| PATH | 36; | COMPONENT | 2; | PATH COST | = | $2513.04 |
| PATH | 36; | COMPONENT | 3; | PATH COST | = | $10052.17 |
| PATH | 36; | COMPONENT | 5; | PATH COST | = | $7539.13 |
| PATH | 36; | COMPONENT | 7; | PATH COST | = | $20104.35 |
| PATH | 36; | COMPONENT | 9; | PATH COST | = | $2513.04 |
| PATH | 36; | COMPONENT | 10; | PATH COST | = | $4013.89 |
| PATH | 36; | COMPONENT | 11; | PATH COST | = | $10052.17 |
| PATH | 40; | COMPONENT | 3; | PATH COST | = | $0.00 |
| PATH | 40; | COMPONENT | 9; | PATH COST | = | $0.00 |
| PATH | 40; | COMPONENT | 10; | PATH COST | = | $0.00 |
| PATH | 42; | COMPONENT | 5; | PATH COST | = | $87072.06 |

*Costs are per component per year in the path indicated. Negative values indicate a return to the maintenance system.

TABLE 4.5b (cont.)

| | | | |
|---|---|---|---|
| PATH 43; | COMPONENT 2; | PATH COST = | $76976.95 |
| PATH 43; | COMPONENT 9; | PATH COST = | $2348.64 |
| PATH 43; | COMPONENT 11; | PATH COST = | $19244.23 |
| PATH 44; | COMPONENT 2; | PATH COST = | $0.00 |
| PATH 44; | COMPONENT 11; | PATH COST = | $0.00 |
| PATH 47; | COMPONENT 12; | PATH COST = | $15902.69 |
| PATH 49; | COMPONENT 4; | PATH COST = | $3499.73 |
| PATH 49; | COMPONENT 6; | PATH COST = | $20998.43 |
| PATH 49; | COMPONENT 7; | PATH COST = | $13998.95 |
| PATH 61; | COMPONENT 7; | PATH COST = | $28388.18 |
| PATH 62; | COMPONENT 4; | PATH COST = | $2072.97 |
| PATH 64; | COMPONENT 4; | PATH COST = | $20609.10 |
| PATH 66; | COMPONENT 7; | PATH COST = | $2072.97 |
| PATH 68; | COMPONENT 6; | PATH COST = | $508.77 |
| PATH 70; | COMPONENT 6; | PATH COST = | $2109.61 |
| PATH 71; | COMPONENT 6; | PATH COST = | $6416.86 |
| PATH 72; | COMPONENT 6; | PATH COST = | $2109.61 |
| PATH 73; | COMPONENT 6; | PATH COST = | $1036.48 |
| PATH 75; | COMPONENT 12; | PATH COST = | $23020.69 |
| PATH 77; | COMPONENT 12; | PATH COST = | $153471.28 |
| | | TOTAL COST = | $1050973.21 |

These path costs are listed in the third column of the table. The costs are the dollars per year required for the component and path indicated.* Where the costs are negative, a return to the maintenance operation is indicated (typically, from the scrap value of a component). At the bottom of the table, the overall yearly operating cost for the base case year is shown. This total yearly cost, for the Metroliner truck, is slightly in excess of $1 million.

The contribution of the various paths and of the various components to the $1.05 million total vary considerably. In Table 4.5b, the major contributions to cost can be readily identified. The top five individual costs are, in order of decreasing cost:

1. The cost to replace brakes (path 23, component 8). This cost is the leading individual cost and accounts for about 15% of the overall yearly maintenance cost.

2. The cost for major overhaul of the traction motors (path 77, component 12).

3. The cost for replacement of gear boxes (path 9, component 6).

---

*It is to be noted that some of the annual costs may differ from those currently being produced by the actual maintenance operation. Such differences between actual costs and those computed by the model are to be expected — the base case has been developed to represent the events of steady state maintenance operation. For this eventual steady state operation, all components are being replaced at a rate which is constant with time. Consequently, the replacement of a component which lasts, say, five years, has been taken to occur uniformly over this period of time in the model. The actual maintenance operation may not be in steady state so that the replacement costs can vary considerably with time (especially if the truck is relatively new). In such a case, the average (over a period of years) eventual yearly cost will be that given by the model.

4. The cost for wheel replacement (path 8, component 7).

5. The costs for truck removal and initial truck disassembly (path 42, component 5).

Combinations of individual costs are also of interest. For example, the total for the periodic, terminal, and in-shop inspection costs (total for paths 30, 32, and 36) is about $117,000. This total inspection cost is sufficiently high that it ranks within the five individual costs given above.

The results given in Tables 4.5a and 4.5b can be considered in a number of ways for the purpose of evaluation. One way to do this is to develop a table which gives the results in a summary form. For the Metroliner, such a table has been prepared and is shown as Table 4.6. This table gives, for the various truck components, the number of units reworked, the number of units scrapped, and the cost of the rework. For the purpose of the table, rework is defined as putting the component into an "as new" condition. Scrapped refers to removal of the component from service. The net cost of rework is the sum of all inspections, disassembly-assembly labor, and parts (including income from scrap). The percent total cost associated with each component is also given. Only maintenance actions which occur in the maintenance facility are included in the table.

It can be seen from the table that the costs associated with rework of the traction motor are greater than those associated with any other component. However, the costs for brakes, wheels, and axles/gear boxes are only slightly smaller than those for motors. It can also be seen that the average cost for truck rework is $1,000,976/1745 = $574.

## TABLE 4.6

### TRUCK MAINTENANCE SHOP SUMMARY FOR METROLINER

(Only maintenance actions which occur in maintenance facility are included)

| COMPONENT NUMBER | TRUCK SUBASSEMBLY REWORKED | NUMBER UNITS REWORKED* | NUMBER UNITS SCRAPPED** | NET COST OF REWORK*** | PERCENT TOTAL COST |
|---|---|---|---|---|---|
| 8 | Brakes | -- | 19,589 | 156,716 | 15.66 |
| 4 | Bearings | 298 | 182 | 52,320 | 5.23 |
| 7 | Wheels | 4380 | 480 | 150,938 | 15.08 |
| 12 | Motors | 76 | -- | 192,394 | 19.22 |
| 6 | Axles/Gear Boxes | 72 G.B. | 50 axles | 157,088 | 15.69 |
| 1,2 | Springs | 370 | 92 | | |
| 3 | Dampers | 278 | 92 | | |
| 5 | Frames | 79 | -- | | |
| 11 | Bolsters | 93 | -- | 291,516 | 29.13 |
| 10 | Alternators | 68 | -- | | |
| 9 | Pneumatics | 68 | 39 | | |
| TOTAL TRUCKS THROUGH SHOP | | 1745 | -- | 1,000,976 | 100% |

*Rework refers to restoring component to an "as new" condition.

**Scrap refers to removal of the component from service.

***Net cost of rework is the cost of all inspections, disassembly-assembly labor, and parts (including income from scrap).

### 4.3.2 Base Case Analysis for the Amcoaches

The base case analysis for the Amcoaches is shown as Tables 4.7a and 4.7b. These tables correspond to Table 4.5a and 4.5b for the Metroliner and the explanations of the content of those tables apply to Tables 4.7a and 4.7b*.

Table 4.7b shows that the total annual cost for Amcoach truck maintenance is computed to be approximately $2.73 million. Of this total, the top five individual contributors are, in order of decreasing cost:

1. The cost for replacement brake parts (path 4, component 8). This cost is the leading individual cost and accounts for about 24% of the overall yearly maintenance cost.

2. The cost for the labor associated with maintenance of the braking system (path 39, component 8).

3. The parts cost for brake discs replaced during overhaul of the wheelsets (path 5, component 6).

4. The parts cost for periodic replacement of the secondary springs (path 4, component 2).

5. The parts cost for wheels replaced during overhaul of the wheelsets (path 5, component 7).

---

*The footnotes in Section 4.3.1 also apply for the Amcoaches.

TABLE 4.7a

BASE CASE ANALYSIS FOR AMCOACHES —

FLOWS AND QUALITIES*

YEAR 0

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| PATH | 1 | COMPONENT | 1 | NUM | = | 3936 | QUALITY = 0.0041 |
| PATH | 1 | COMPONENT | 2 | NUM | = | 1968 | QUALITY = 0.0458 |
| PATH | 1 | COMPONENT | 3 | NUM | = | 3936 | QUALITY = 0.0099 |
| PATH | 1 | COMPONENT | 4 | NUM | = | 3936 | QUALITY = 0.0083 |
| PATH | 1 | COMPONENT | 5 | NUM | = | 1968 | QUALITY = 0.0014 |
| PATH | 1 | COMPONENT | 6 | NUM | = | 3936 | QUALITY = 0.0041 |
| PATH | 1 | COMPONENT | 7 | NUM | = | 3936 | QUALITY = 0.0250 |
| PATH | 1 | COMPONENT | 8 | NUM | = | 3936 | QUALITY = 0.0833 |
| PATH | 1 | COMPONENT | 9 | NUM | = | 1968 | QUALITY = 0.0041 |
| PATH | 1 | COMPONENT | 10 | NUM | = | 1968 | QUALITY = 0.0041 |
| PATH | 1 | COMPONENT | 11 | NUM | = | 984 | QUALITY = 0.0416 |
| PATH | 1 | COMPONENT | 12 | NUM | = | 1 | QUALITY = 1.0000 |
| PATH | 4 | COMPONENT | 2 | NUM/YR | = | 394 | QUALITY = 0.0000 |
| PATH | 4 | COMPONENT | 5 | NUM/YR | = | 130 | QUALITY = 0.0000 |
| PATH | 4 | COMPONENT | 8 | NUM/YR | = | 15743 | QUALITY = 0.0000 |
| PATH | 4 | COMPONENT | 10 | NUM/YR | = | 393 | QUALITY = 0.0000 |
| PATH | 5 | COMPONENT | 1 | NUM/YR | = | 787 | QUALITY = 0.0000 |
| PATH | 5 | COMPONENT | 4 | NUM/YR | = | 787 | QUALITY = 0.0000 |
| PATH | 5 | COMPONENT | 6 | NUM/YR | = | 787 | QUALITY = 0.0000 |
| PATH | 5 | COMPONENT | 7 | NUM/YR | = | 787 | QUALITY = 0.0000 |
| PATH | 16 | COMPONENT | 2 | NUM/YR | = | 394 | QUALITY = 1.0000 |
| PATH | 16 | COMPONENT | 5 | NUM/YR | = | 130 | QUALITY = 0.9999 |
| PATH | 16 | COMPONENT | 8 | NUM/YR | = | 15743 | QUALITY = 1.0000 |
| PATH | 16 | COMPONENT | 10 | NUM/YR | = | 393 | QUALITY = 0.9999 |
| PATH | 17 | COMPONENT | 1 | NUM/YR | = | 787 | QUALITY = 0.0050 |
| PATH | 17 | COMPONENT | 4 | NUM/YR | = | 787 | QUALITY = 0.0100 |
| PATH | 17 | COMPONENT | 6 | NUM/YR | = | 787 | QUALITY = 0.0050 |
| PATH | 17 | COMPONENT | 7 | NUM/YR | = | 787 | QUALITY = 0.7000 |
| PATH | 30 | COMPONENT | 1 | NUM/YR | = | 1436640 | QUALITY = 0.0041 |
| PATH | 30 | COMPONENT | 2 | NUM/YR | = | 718320 | QUALITY = 0.0458 |
| PATH | 30 | COMPONENT | 3 | NUM/YR | = | 1436640 | QUALITY = 0.0099 |
| PATH | 30 | COMPONENT | 4 | NUM/YR | = | 1436640 | QUALITY = 0.0083 |
| PATH | 30 | COMPONENT | 5 | NUM/YR | = | 718320 | QUALITY = 0.0014 |
| PATH | 30 | COMPONENT | 6 | NUM/YR | = | 1436640 | QUALITY = 0.0041 |
| PATH | 30 | COMPONENT | 7 | NUM/YR | = | 1436640 | QUALITY = 0.0250 |
| PATH | 30 | COMPONENT | 8 | NUM/YR | = | 1436640 | QUALITY = 0.0833 |

*Paths and components listed are those for which non-zero flows occur.

TABLE 4.7a (cont.)

| | | | |
|---|---|---|---|
| PATH 30 | COMPONENT 9 | NUM/YR = 718320 | QUALITY = 0.0041 |
| PATH 30 | COMPONENT 10 | NUM/YR = 718320 | QUALITY = 0.0041 |
| PATH 30 | COMPONENT 11 | NUM/YR = 359160 | QUALITY = 0.0416 |
| PATH 30 | COMPONENT 12 | NUM/YR = 365 | QUALITY = 1.0000 |
| PATH 31 | COMPONENT 1 | NUM/YR =1311116 | QUALITY = 0.0041 |
| PATH 31 | COMPONENT 2 | NUM/YR = 655558 | QUALITY = 0.0452 |
| PATH 31 | COMPONENT 3 | NUM/YR =1311116 | QUALITY = 0.0097 |
| PATH 31 | COMPONENT 4 | NUM/YR =1311116 | QUALITY = 0.0082 |
| PATH 31 | COMPONENT 5 | NUM/YR = 655558 | QUALITY = 0.0014 |
| PATH 31 | COMPONENT 6 | NUM/YR =1311116 | QUALITY = 0.0041 |
| PATH 31 | COMPONENT 7 | NUM/YR =1311116 | QUALITY = 0.0246 |
| PATH 31 | COMPONENT 8 | NUM/YR =1311116 | QUALITY = 0.0823 |
| PATH 31 | COMPONENT 9 | NUM/YR = 655558 | QUALITY = 0.0041 |
| PATH 31 | COMPONENT 10 | NUM/YR = 655558 | QUALITY = 0.0041 |
| PATH 31 | COMPONENT 11 | NUM/YR = 327779 | QUALITY = 0.0411 |
| PATH 31 | COMPONENT 12 | NUM/YR = 365 | QUALITY = 1.0000 |
| PATH 32 | COMPONENT 1 | NUM/YR = 47232 | QUALITY = 0.0041 |
| PATH 32 | COMPONENT 2 | NUM/YR = 23616 | QUALITY = 0.0458 |
| PATH 32 | COMPONENT 3 | NUM/YR = 47232 | QUALITY = 0.0099 |
| PATH 32 | COMPONENT 4 | NUM/YR = 47232 | QUALITY = 0.0083 |
| PATH 32 | COMPONENT 5 | NUM/YR = 23616 | QUALITY = 0.0014 |
| PATH 32 | COMPONENT 6 | NUM/YR = 47232 | QUALITY = 0.0041 |
| PATH 32 | COMPONENT 7 | NUM/YR = 47232 | QUALITY = 0.0250 |
| PATH 32 | COMPONENT 8 | NUM/YR = 47232 | QUALITY = 0.0833 |
| PATH 32 | COMPONENT 9 | NUM/YR = 23616 | QUALITY = 0.0041 |
| PATH 32 | COMPONENT 10 | NUM/YR = 23616 | QUALITY = 0.0041 |
| PATH 32 | COMPONENT 11 | NUM/YR = 11808 | QUALITY = 0.0416 |
| PATH 32 | COMPONENT 12 | NUM/YR = 12 | QUALITY = 1.0000 |
| PATH 33 | COMPONENT 1 | NUM/YR = 16032 | QUALITY = 0.0000 |
| PATH 33 | COMPONENT 2 | NUM/YR = 8016 | QUALITY = 0.0000 |
| PATH 33 | COMPONENT 3 | NUM/YR = 16032 | QUALITY = 0.0000 |
| PATH 33 | COMPONENT 4 | NUM/YR = 16032 | QUALITY = 0.0000 |
| PATH 33 | COMPONENT 5 | NUM/YR = 8016 | QUALITY = 0.0000 |
| PATH 33 | COMPONENT 6 | NUM/YR = 16032 | QUALITY = 0.0000 |
| PATH 33 | COMPONENT 7 | NUM/YR = 16032 | QUALITY = 0.0000 |
| PATH 33 | COMPONENT 8 | NUM/YR = 16032 | QUALITY = 0.0000 |
| PATH 33 | COMPONENT 9 | NUM/YR = 8016 | QUALITY = 0.0000 |
| PATH 33 | COMPONENT 10 | NUM/YR = 8016 | QUALITY = 0.0000 |
| PATH 33 | COMPONENT 11 | NUM/YR = 4008 | QUALITY = 0.0000 |
| PATH 33 | COMPONENT 12 | NUM/YR = 12 | QUALITY = 1.0000 |

TABLE 4.7a (cont.)

| | | | |
|---|---|---|---|
| PATH 34 | COMPONENT 1 | NUM/YR = 31199 | QUALITY = 0.0063 |
| PATH 34 | COMPONENT 2 | NUM/YR = 15599 | QUALITY = 0.0693 |
| PATH 34 | COMPONENT 3 | NUM/YR = 31199 | QUALITY = 0.0149 |
| PATH 34 | COMPONENT 4 | NUM/YR = 31199 | QUALITY = 0.0126 |
| PATH 34 | COMPONENT 5 | NUM/YR = 15599 | QUALITY = 0.0022 |
| PATH 34 | COMPONENT 6 | NUM/YR = 31199 | QUALITY = 0.0063 |
| PATH 34 | COMPONENT 7 | NUM/YR = 31199 | QUALITY = 0.0378 |
| PATH 34 | COMPONENT 8 | NUM/YR = 31199 | QUALITY = 0.1261 |
| PATH 34 | COMPONENT 9 | NUM/YR = 15599 | QUALITY = 0.0063 |
| PATH 34 | COMPONENT 10 | NUM/YR = 15599 | QUALITY = 0.0063 |
| PATH 34 | COMPONENT 11 | NUM/YR = 7799 | QUALITY = 0.0630 |
| PATH 35 | COMPONENT 1 | NUM/YR = 125523 | QUALITY = 0.0047 |
| PATH 35 | COMPONENT 2 | NUM/YR = 62761 | QUALITY = 0.0517 |
| PATH 35 | COMPONENT 3 | NUM/YR = 125523 | QUALITY = 0.0111 |
| PATH 35 | COMPONENT 4 | NUM/YR = 125523 | QUALITY = 0.0094 |
| PATH 35 | COMPONENT 5 | NUM/YR = 62761 | QUALITY = 0.0016 |
| PATH 35 | COMPONENT 6 | NUM/YR = 125523 | QUALITY = 0.0047 |
| PATH 35 | COMPONENT 7 | NUM/YR = 125523 | QUALITY = 0.0282 |
| PATH 35 | COMPONENT 8 | NUM/YR = 125523 | QUALITY = 0.0940 |
| PATH 35 | COMPONENT 9 | NUM/YR = 62761 | QUALITY = 0.0047 |
| PATH 35 | COMPONENT 10 | NUM/YR = 62761 | QUALITY = 0.0047 |
| PATH 35 | COMPONENT 11 | NUM/YR = 31380 | QUALITY = 0.0470 |
| PATH 36 | COMPONENT 1 | NUM/YR = 156723 | QUALITY = 0.0050 |
| PATH 36 | COMPONENT 2 | NUM/YR = 78361 | QUALITY = 0.0552 |
| PATH 36 | COMPONENT 3 | NUM/YR = 156723 | QUALITY = 0.0119 |
| PATH 36 | COMPONENT 4 | NUM/YR = 156723 | QUALITY = 0.0100 |
| PATH 36 | COMPONENT 5 | NUM/YR = 78361 | QUALITY = 0.0017 |
| PATH 36 | COMPONENT 6 | NUM/YR = 156723 | QUALITY = 0.0050 |
| PATH 36 | COMPONENT 7 | NUM/YR = 156723 | QUALITY = 0.0301 |
| PATH 36 | COMPONENT 8 | NUM/YR = 156723 | QUALITY = 0.1004 |
| PATH 36 | COMPONENT 9 | NUM/YR = 78361 | QUALITY = 0.0050 |
| PATH 36 | COMPONENT 10 | NUM/YR = 78361 | QUALITY = 0.0050 |
| PATH 36 | COMPONENT 11 | NUM/YR = 39180 | QUALITY = 0.0502 |
| PATH 37 | COMPONENT 1 | NUM/YR = 787 | QUALITY = 0.0050 |
| PATH 37 | COMPONENT 2 | NUM/YR = 394 | QUALITY = 1.0000 |
| PATH 37 | COMPONENT 4 | NUM/YR = 787 | QUALITY = 0.0100 |
| PATH 37 | COMPONENT 5 | NUM/YR = 130 | QUALITY = 0.9999 |
| PATH 37 | COMPONENT 6 | NUM/YR = 787 | QUALITY = 0.0050 |
| PATH 37 | COMPONENT 7 | NUM/YR = 787 | QUALITY = 0.7000 |
| PATH 37 | COMPONENT 8 | NUM/YR = 156723 | QUALITY = 0.1004 |
| PATH 37 | COMPONENT 10 | NUM/YR = 78361 | QUALITY = 0.0050 |

TABLE 4.7a (cont.)

| | | | |
|---|---|---|---|
| PATH 38 | COMPONENT 1 | NUM/YR = 155936 | QUALITY = 0.0050 |
| PATH 38 | COMPONENT 2 | NUM/YR = 77967 | QUALITY = 0.0504 |
| PATH 38 | COMPONENT 3 | NUM/YR = 156723 | QUALITY = 0.0119 |
| PATH 38 | COMPONENT 4 | NUM/YR = 155936 | QUALITY = 0.0100 |
| PATH 38 | COMPONENT 5 | NUM/YR = 78230 | QUALITY = 0.0001 |
| PATH 38 | COMPONENT 6 | NUM/YR = 155936 | QUALITY = 0.0050 |
| PATH 38 | COMPONENT 7 | NUM/YR = 155936 | QUALITY = 0.0267 |
| PATH 38 | COMPONENT 9 | NUM/YR = 78361 | QUALITY = 0.0050 |
| PATH 38 | COMPONENT 11 | NUM/YR = 39180 | QUALITY = 0.0502 |
| PATH 39 | COMPONENT 2 | NUM/YR = 394 | QUALITY = 1.0000 |
| PATH 39 | COMPONENT 5 | NUM/YR = 130 | QUALITY = 0.9999 |
| PATH 39 | COMPONENT 8 | NUM/YR = 156723 | QUALITY = 0.1004 |
| PATH 39 | COMPONENT 10 | NUM/YR = 78361 | QUALITY = 0.0050 |
| PATH 40 | COMPONENT 8 | NUM/YR = 140979 | QUALITY = 0.0000 |
| PATH 40 | COMPONENT 10 | NUM/YR = 77967 | QUALITY = 0.0000 |
| PATH 41 | COMPONENT 2 | NUM/YR = 394 | QUALITY = 0.0000 |
| PATH 41 | COMPONENT 5 | NUM/YR = 130 | QUALITY = 0.0000 |
| PATH 41 | COMPONENT 8 | NUM/YR = 156723 | QUALITY = 0.0000 |
| PATH 41 | COMPONENT 10 | NUM/YR = 78361 | QUALITY = 0.0000 |
| PATH 42 | COMPONENT 1 | NUM/YR = 787 | QUALITY = 0.0050 |
| PATH 42 | COMPONENT 4 | NUM/YR = 787 | QUALITY = 0.0100 |
| PATH 42 | COMPONENT 6 | NUM/YR = 787 | QUALITY = 0.0050 |
| PATH 42 | COMPONENT 7 | NUM/YR = 787 | QUALITY = 0.7000 |
| PATH 45 | COMPONENT 1 | NUM/YR = 787 | QUALITY = 0.0000 |
| PATH 45 | COMPONENT 4 | NUM/YR = 787 | QUALITY = 0.0000 |
| PATH 45 | COMPONENT 6 | NUM/YR = 787 | QUALITY = 0.0000 |
| PATH 45 | COMPONENT 7 | NUM/YR = 787 | QUALITY = 0.0000 |
| PATH 58 | COMPONENT 1 | NUM/YR = 787 | QUALITY = 0.0000 |
| PATH 58 | COMPONENT 2 | NUM/YR = 394 | QUALITY = 0.0000 |
| PATH 58 | COMPONENT 4 | NUM/YR = 787 | QUALITY = 0.0000 |
| PATH 58 | COMPONENT 5 | NUM/YR = 130 | QUALITY = 0.0000 |
| PATH 58 | COMPONENT 6 | NUM/YR = 787 | QUALITY = 0.0000 |
| PATH 58 | COMPONENT 7 | NUM/YR = 787 | QUALITY = 0.0000 |
| PATH 58 | COMPONENT 8 | NUM/YR = 156723 | QUALITY = 0.0000 |
| PATH 58 | COMPONENT 10 | NUM/YR = 78361 | QUALITY = 0.0000 |
| PATH 59 | COMPONENT 1 | NUM/YR = 156723 | QUALITY = 0.0049 |

TABLE 4.7a (cont.)

| | | | |
|---|---|---|---|
| PATH 59 | COMPONENT 2 | NUM/YR = 78361 | QUALITY = 0.0502 |
| PATH 59 | COMPONENT 3 | NUM/YR = 156723 | QUALITY = 0.0119 |
| PATH 59 | COMPONENT 4 | NUM/YR = 156723 | QUALITY = 0.0099 |
| PATH 59 | COMPONENT 5 | NUM/YR = 78361 | QUALITY = 0.0001 |
| PATH 59 | COMPONENT 6 | NUM/YR = 156723 | QUALITY = 0.0049 |
| PATH 59 | COMPONENT 7 | NUM/YR = 156723 | QUALITY = 0.0266 |
| PATH 59 | COMPONENT 8 | NUM/YR = 156723 | QUALITY = 0.0000 |
| PATH 59 | COMPONENT 9 | NUM/YR = 78361 | QUALITY = 0.0050 |
| PATH 59 | COMPONENT 10 | NUM/YR = 78361 | QUALITY = 0.0000 |
| PATH 59 | COMPONENT 11 | NUM/YR = 39180 | QUALITY = 0.0502 |
| PATH 60 | COMPONENT 1 | NUM/YR = 156723 | QUALITY = 0.0049 |
| PATH 60 | COMPONENT 2 | NUM/YR = 78361 | QUALITY = 0.0502 |
| PATH 60 | COMPONENT 3 | NUM/YR = 156723 | QUALITY = 0.0119 |
| PATH 60 | COMPONENT 4 | NUM/YR = 156723 | QUALITY = 0.0099 |
| PATH 60 | COMPONENT 5 | NUM/YR = 78361 | QUALITY = 0.0001 |
| PATH 60 | COMPONENT 6 | NUM/YR = 156723 | QUALITY = 0.0049 |
| PATH 60 | COMPONENT 7 | NUM/YR = 156723 | QUALITY = 0.0266 |
| PATH 60 | COMPONENT 8 | NUM/YR = 156723 | QUALITY = 0.0000 |
| PATH 60 | COMPONENT 9 | NUM/YR = 78361 | QUALITY = 0.0050 |
| PATH 60 | COMPONENT 10 | NUM/YR = 78361 | QUALITY = 0.0000 |
| PATH 60 | COMPONENT 11 | NUM/YR = 39180 | QUALITY = 0.0502 |

TABLE 4.7b

BASE CASE ANALYSIS FOR AMCOACHES — COSTS*

| | | | | | |
|---|---|---|---|---|---|
| PATH | 4; | COMPONENT | 2; | PATH COST = | $157601.37 |
| PATH | 4; | COMPONENT | 5; | PATH COST = | $261.99 |
| PATH | 4; | COMPONENT | 8; | PATH COST = | $661247.81 |
| PATH | 4; | COMPONENT | 10; | PATH COST = | $19699.88 |
| PATH | 5; | COMPONENT | 1; | PATH COST = | $31484.82 |
| PATH | 5; | COMPONENT | 4; | PATH COST = | $59034.03 |
| PATH | 5; | COMPONENT | 6; | PATH COST = | $314848.21 |
| PATH | 5; | COMPONENT | 7; | PATH COST = | $157424.10 |
| PATH | 17; | COMPONENT | 4; | PATH COST = | $-4722.72 |
| PATH | 17; | COMPONENT | 6; | PATH COST = | $-787.12 |
| PATH | 17; | COMPONENT | 7; | PATH COST = | $-15742.41 |
| PATH | 30; | COMPONENT | 2; | PATH COST = | $86198.40 |
| PATH | 30; | COMPONENT | 5; | PATH COST = | $17239.68 |
| PATH | 30; | COMPONENT | 7; | PATH COST = | $138779.42 |
| PATH | 30; | COMPONENT | 8; | PATH COST = | $138779.42 |
| PATH | 32; | COMPONENT | 2; | PATH COST = | $22671.36 |
| PATH | 32; | COMPONENT | 5; | PATH COST = | $14169.60 |
| PATH | 32; | COMPONENT | 7; | PATH COST = | $25505.28 |
| PATH | 32; | COMPONENT | 8; | PATH COST = | $26449.92 |
| PATH | 32; | COMPONENT | 9; | PATH COST = | $4250.88 |
| PATH | 38; | COMPONENT | 2; | PATH COST = | $34006.98 |
| PATH | 38; | COMPONENT | 3; | PATH COST = | $4043.51 |
| PATH | 38; | COMPONENT | 4; | PATH COST = | $4513.20 |
| PATH | 38; | COMPONENT | 5; | PATH COST = | $233.07 |
| PATH | 38; | COMPONENT | 7; | PATH COST = | $54027.05 |
| PATH | 38; | COMPONENT | 9; | PATH COST = | $3404.14 |
| PATH | 38; | COMPONENT | 11; | PATH COST = | $33987.32 |
| PATH | 39; | COMPONENT | 2; | PATH COST = | $108871.03 |
| PATH | 39; | COMPONENT | 5; | PATH COST = | $4519.48 |
| PATH | 39; | COMPONENT | 8; | PATH COST = | $587251.03 |
| PATH | 39; | COMPONENT | 10; | PATH COST = | $4456.11 |
| PATH | 42; | COMPONENT | 7; | PATH COST = | $40780.71 |

TOTAL COST = $2734487.64

*Costs are per component per year in the path indicated. Negative values indicate a return to the maintenance system.

As for the Metroliner, the total of the various individual inspection costs is considerable. The total cost for the periodic inspections (total cost for path 32) is about $93,000. The total cost for the terminal inspection is about $381,000. Together, these inspection costs amount to about $474,000. This total inspection cost is sufficiently high that, as for the Metroliner, it ranks within the five individual costs given above.

## 5. CONSIDERATION OF ALTERNATIVES

This section is concerned with the use of the simulation cost model to determine the effects on the operation and on the cost of the truck maintenance system produced by time or by changes in system characteristics. The system characteristics can include maintenance policies, labor practices, specifications, etc. In making these determinations, a sensitivity analysis is useful. The sensitivity analysis is described in Section 5.1 and includes results for the Metroliner and Amcoach trucks. These sensitivity analyses and their associated base cases are then employed in Section 5.2 to show how the effects of changes in system characteristics are obtained. Illustrative specifications which could be appropriate for passenger train trucks are also included in the section for this purpose. In Section 5.3, the use of the simulation cost model in its simulation or predictive capacity is considered.

### 5.1 Sensitivity Analysis

The sensitivity analysis is the change in annual maintenance system operating cost produced by a change in the value of a parameter in the cost model. For the Metroliner and Amcoach models, sensitivity analyses were produced using the base cases (Section 4.3) as the reference. The parameters considered to be of most interest for these sensitivity analyses are C, D, E, and K$ and the path costs. Results for the Metroliner and Amcoach models are shown in Tables 5.1 and 5.2.*

The tables give five columns. In the first column is the node number (obtained by counting all nodes — branch, summation, and extra). This number is that in the schematic diagram. In the second column is the branch node number (obtained by counting only the branch nodes). The third column gives the component under consideration for the sensitivity

*See Section 3.3 for additional discussion of the sensitivity analysis.

TABLE 5.1

DECISION PARAMETER

SENSITIVITY RESULTS FOR THE METROLINER

| Node Number | Branch Node Number | Component | Sensitivity* ($/%) | Parameter |
|---|---|---|---|---|
| 1 | 1 | 1 | $ 74.21 | C |
| | | 2 | 202.04 | C |
| | | 3 | 68.36 | C |
| | | 4 | 97.75 | C |
| | | 5 | 360.93 | C |
| | | 6 | 273.90 | C |
| | | 7 | 394.91 | C |
| | | 9 | 36.07 | C |
| | | 10 | 22.79 | C |
| | | 11 | 75.87 | C |
| | | 12 | 413.08 | C |
| 2 | 2 | 1 | 211.10 | C |
| | | 2 | 731.23 | C |
| | | 3 | 168.65 | C |
| | | 4 | 425.58 | C |
| | | 5 | 585.17 | C |
| | | 6 | 1,297.20 | C |
| | | 7 | 1,114.78 | C |
| | | 9 | 110.40 | C |
| | | 10 | 51.21 | C |
| | | 11 | 217.09 | C |
| | | 12 | 1,510.87 | C |
| 3 | 3 | 8 | 1,567.16 | C |

*If a sensitivity result is not given for a component or identifiable subassembly at a node, the sensitivity is $0.00/%.

Table 5.1 (continued)

| Node Number | Branch Node Number | Component | Sensitivity ($/%) | Parameter |
|---|---|---|---|---|
| 4 | 4 | 8 | $1,567.16 | D |
| 6 | 5 | 1 | 2,021.30 | * |
| 7 | 6 | 1 | 6,421.21 | * |
| 10 | 7 | 1 | 7,774.17 | * |
| 11 | 8 | 1 | 7,482.44 | * |
| | | 9 | 121.34 | D |
| 12 | 9 | 3 | 136.50 | D |
| | | 10 | 33.87 | D |
| 14 | 10 | 1 | 5,511.15 | * |
| 15 | 11 | 2 | 138.36 | D |
| | | 9 | 97.86 | D |
| 20 | 12 | 1 | 3,587.20 | * |
| | | 12 | -4,832.71 | E |
| 22 | 13 | 4 | 3,402.41 | * |
| 23 | 14 | 4 | 1,226.31 | * |
| 24 | 15 | 1 | 184.79 | D |
| 30 | 16 | 6 | 2,245.35 | * |
| 31 | 17 | 4 | 135.99 | D |

TABLE 5.2

DECISION PARAMETER

SENSITIVITY RESULTS FOR THE AMCOACHES

| Node Number | Branch Node Number | Component | Sensitivity *($/%) | Parameter |
|---|---|---|---|---|
| 1 | 1 | 1 | 62.67 | C |
| | | 2 | 977.56 | C |
| | | 3 | 10.10 | C |
| | | 4 | 119.41 | C |
| | | 5 | 154.23 | C |
| | | 6 | 625.22 | C |
| | | 7 | 958.70 | C |
| | | 8 | 3,385.74 | C |
| | | 9 | 51.06 | C |
| | | 10 | 60.69 | C |
| | | 11 | 84.96 | C |
| 2 | 2 | 1 | 252.16 | C |
| | | 2 | 3,115.92 | C |
| | | 3 | 30.32 | C |
| | | 4 | 468.83 | C |
| | | 5 | 210.00 | C |
| | | 6 | 2,515.39 | C |
| | | 7 | 3,048.18 | C |
| | | 8 | 10,751.53 | C |
| | | 9 | 25.48 | C |
| | | 10 | 180.86 | C |
| | | 11 | 254.90 | C |
| 6 | 3 | 1 | 5,559.63 | * |

*If a sensitivity result is not given for a component or identifiable subassembly at a node, the sensitivity is $0.00/%.

Table 5.2 (continued)

| Node Number | Branch Node Number | Component | Sensitivity *($/%) | Parameter |
|---|---|---|---|---|
| 7 | 4 | 1 | $17,044.79 | * |
| 10 | 5 | 1 | 5,751.61 | * |
| | | 2 | 2,630.68 | D |
| | | 5 | 13.88 | D |
| | | 8 | 12,484.98 | D |
| | | 10 | 241.56 | D |
| 11 | 6 | 1 | 5,823.19 | * |
| 12 | 7 | 2 | 1,576.01 | D |
| | | 5 | 2.61 | D |
| | | 8 | 6,612.47 | D |
| | | 10 | 196.99 | D |
| 15 | 8 | 1 | 5,415.38 | * |

analysis. For a component which is part of an identifiable subassembly at the node, the component number is the lowest of those comprising the subassembly. The sensitivity is given in Column 4. The value given is in terms of dollars per percent, where these are defined as follows:

- o The dollars are the increased total annual cost for the entire maintenance system described by the schematic diagram and by the associated base case analysis. All interactions among flows and among components are included in this increased cost.
- o The percent refers to a one percent increase in a flow on the path intended for defective* components. Referring to the data given in lines 9230 through 9269 (see Appendix A), this path is the one given second at each node. The one percent increase can be for the units branching to the defective path (C decision), for the defective units correctly identified as defective (D decision), for the good units incorrectly identified as defective (E decision), or for the number of identifiable subassemblies branching to the defective path (K$ parameter).

That parameter which has had its value increased for the sensitivity result is indicated in the last column of the table. For the K$ parameter, the symbol "*" is used.

It is to be noted that only decision parameter sensitivity results are given in the table. Cost path sensitivities are not given. The cost path sensitivity is the change in annual maintenance system operating cost produced by a 1% increase in a path cost. This sensitivity is useful in indicating how individual costs (rather than maintenance

*The term "defective" is used merely to identify this outgoing path.

procedures which affect the decision parameters, path flows, and qualities) affect the total annual cost.

The cost path sensitivities can be provided by the simulation cost model. However, the same information can be obtained directly from the base case analysis by moving the decimal point two places to the left in Tables 4.5b and 4.7b. This technique is applicable because each cost path sensitivity is obtained by varying only the unit cost in a given path -- no changes in path flows, qualities, or costs on paths other than the one under consideration occur.

To describe the meaning of the decision parameter sensitivity analyses, node 11 (branch node 8) can be considered. The first sensitivity result given (Table 5.1) is for component 1, which is part of an identifiable subassembly (this is denoted by the *). The components in the subassembly at the node are 1, 2, 4, 5, 6, 7, 8, 11, 12 (see Table 3.2). The sensitivity result is $7,482.44/%. This means that for a 1% increase in the flow of this subassembly in path 39 (and, necessarily, a corresponding decrease in the flow of this subassembly in path 42) the total annual Metroliner maintenance cost will increase by $7,482.44. The second sensitivity result is $121.35/% and is for a D decision. Consequently, if the number of defective pneumatic systems branching to path 39 is increased by 1%, the total annual Metroliner maintenance cost will increase by $121.34.

A similar meaning is associated with the cost path sensitivities. For the Metroliner, the cost path sensitivity for component 7 (wheels) on path 36 (inspection) is $201.04/%. This indicates that a 1% increase in that inspection cost produces an annual cost increase of $201.04.

## 5.2 Use of the Sensitivity Analyses

The sensitivity analyses can be used to indicate which aspects of maintenance system operation contribute strongly to costs. Also, the analyses can indicate which aspects require only small modifications to produce significant cost reductions. Both uses provide evaluations of the cost effects of specifications as discussed later in this section.

Those aspects of maintenance system operation which contribute strongly to costs can be determined from the cost path sensitivities. As discussed in Section 5.1, these sensitivities are obtained directly from the base case cost results (Tables 4.5b and 4.7b) and contain the same information as is in those results. The major contributors to cost can therefore be obtained by considering Tables 4.5b and 4.7b from either a base case or a cost path sensitivity point of view. With respect to the Metroliner and Amcoach trucks, the major contributors to costs are given in Section 4.3.

Those aspects of maintenance system operation which for small modifications produce large cost reductions are typically identified from the decision parameter sensitivities. A review of the sensitivity results given in Table 5.1 indicates that important cost-sensitive areas are:

- trucks sent to maintenance for periodic inspections and because of bad-orders at terminals (nodes 6 and 7). The sensitivity for the combination of both nodes gives \$8,442.71 per percent sent for maintenance. In the base case, 1745 trucks are sent for maintenance per year (path 36). A 1% decrease in this flow (about 17 trucks) saves \$8,442.71.
- trucks in the shop requiring maintenance (node 10). This sensitivitiy is \$7774.17/%. In the base case, the 1745 trucks entering the maintenance facility undergo maintenance. If this flow is decreased by 1% (about 17 trucks) a savings of \$7774.17 results.

- trucks sent to "truck shop" (node 14). These trucks contain only primary springs, bearings, frames, axles/ gear boxes, or motors. Some of these "stripped" trucks require service — the remainder are associated with maintenance to the other components in the "car shop." The sensitivity is $5,511.15/% of trucks sent to the truck shop.
- trucks in the "truck shop" after those electric motors requiring maintenance have been removed (node 20). The sensitivity is $3,587.20/% of such trucks on path 48.
- wheelsets sent to the wheel shop for service (node 22). In the base case analysis, 2430 wheel sets (for 1215 trucks) are sent to the wheel shop. If this flow is decreased by 1% (about 24 wheel sets) a savings of $3,402.41 results.

The meaning of these sensitivity analysis results can be illustrated by means of Table 5.3. This table gives five columns, the first being a list of maintenance actions taken. The truck components involved in each maintenance action are listed in the second column. Sensitivity numbers are presented in Column 3. The table shows that a 1% decrease in the number of trucks maintained in the maintenance facility produces a cost savings of $7,774. After maintenance of secondary springs, dampers, alternators, pneumatics, and bolsters, the sensitivity is $5,511. This number is lower than the first ($7,774) and shows annual cost effect of maintenance on the remaining components. After motors have been serviced, the sensitivity reduces to $3,587/%. This sensitivity is that for maintaining the components still lower in the table (primary springs, frames, and wheelsets). After springs and frames have been serviced, the sensitivity reduces to $3,402/%. This sensitivity is that associated with maintenance of the wheelsets alone.

TABLE 5.3

TRUCK MAINTENANCE COST SENSITIVITIES

ANNUAL TOTALS

| Maintenance Repairs Required | Truck Components Maintained | Cost Sensitivity $/Percent | Cost Sensitivity $/Truck-In** |
|---|---|---|---|
| All In-Shop Repairs* | | 7774 | 446 |
| | Secondary Springs | | |
| | Dampers | | |
| | Alternators | | |
| | Pneumatics | | |
| | Bolsters | | |
| After Above Repairs* | | 5511 | 316 |
| | Motors | | |
| After Above Repairs* | | 3587 | 205 |
| | Primary Springs | | |
| | Frames | | |
| After Above Repairs* | | 3402 | 195 |
| | Bearings | | |
| | Wheels | | |
| | Axles/Gear Boxes | | |

*Maintenance includes all components listed below this line.

**Truck-In refers to those trucks which enter the service facility per year (in this case, 1745 trucks).

In the last column of the table, a cost sensitivity per truck is given. These numbers are those given in Column 3 divided by 1745 (the number of trucks per year which enter the service facility).

A further description of these sensitivity results can be provided with a diagram. Such a diagram is given in Figure 5.1. This figure shows, schematically, the flows of trucks into the service facility and to the various maintenance areas. The sensitivity analysis results are given in the boxes which denote the levels of service actions. The figure shows that as more components have been maintained (toward the right side of the figure), the sensitivity costs decrease. This is to be expected because few maintenance actions occur as one proceeds from left to right in the diagram.

The Amcoach sensitivity analysis results can be considered in a manner similar to that for the Metroliner. From Table 5.2 the sensitivities for the combination of nodes 6 and 7 are $22,604.42/% ($5,559.63/% + $17,044.79/%). This sensitivity indicates that a 1% decrease in the number of trucks sent for maintenance (a 391 truck decrease) would save $22,604.42. The sensitivity for node 10 is, for the Amcoach model, given separately for components 2, 5, 8, and 10 and for subassembly 1, wheelsets (containing components 1, 4, 6, and 7). A 1% decrease in the number of wheelsets sent for major service (a decrease of about four wheelsets) would save $5,751.61. A 1% decrease in the number of secondary springs, side frames (wear pads), brake assemblies, and speed sensors/decelostats requiring service (decreases of about 5, 1, 158, and 4 units, respectively*) would save $2,630.68, $13.88, $12,484.98, and

*The sensitivity shown in Table 5.2 for these components is for a D decision. Consequently, the 1% decrease is for the number of defective units in path 37, not for a 1% decrease in the number of total units in that path.

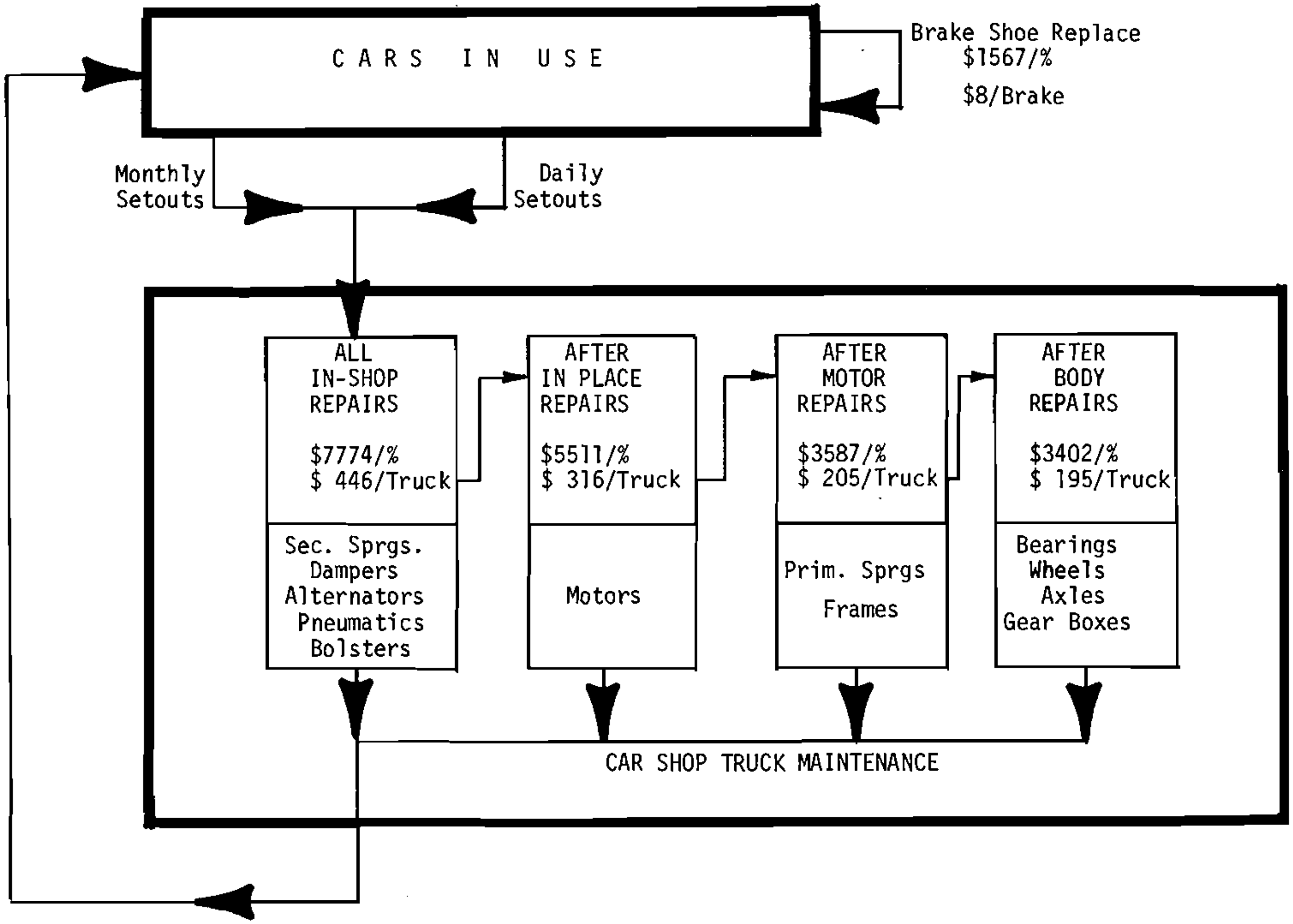


FIGURE 5.1 SCHEMATIC DIAGRAM OF CAR SHOP FLOWS OF TRUCK MAINTENANCE
(FOUR STAGES OF REWORK ARE SHOWN WITH ASSOCIATED ANNUAL COST SENSITIVITES)

$241.56 respectively. A 1% decrease in the number of wheelsets serviced (a decrease of about 35 wheelsets) would save $5,823.19. As in the case of the Metroliner the sensitivity analysis results tend to decrease in magnitude with increasing node numbers. This occurs because few maintenance actions remain to be done as one proceeds through the schematic diagrams.

The path cost and decision sensitivity results given above indicate the capability of sensitivity analysis to pinpoint cost consequences of changes in the maintenance system. This capability is relevant to specifications which may be developed for the purpose of influencing truck maintenance costs. The relationship between the sensitivity analysis and such specifications can be developed by considering specifications which are illustrative in nature. One illustrative specification is as follows.

A specification is developed which requires that some of the truck components and assemblies be certified or undergo acceptance testing. The specification also addresses, for the certification or acceptance testing, its relative stringency for the various components and assemblies. The specification does not name the particular components and assemblies that are to be tested or certified. Instead, the specification requires that the simulation cost model be applied to the truck, and the rules for this application are provided. The resulting base case* and sensitivity analyses are then used to indicate which components most affect the yearly operating costs. These components are then required to be certified or to be subjected to testing. The base case and sensitivity analysis also suggest the reasons why these components have the proportionately high operating costs. This information is used to select the particular certification procedure or acceptance tests to be used for the components.

The application of this illustrative specification to the Metroliner, for example, need involve only the path cost sensitivities (as opposed to the decision parameter sensitivities). Referring to the sensitivity discussion in Section 5.2 and to the base case results in Section 4.3, it can be seen that the four most important path cost sensitivities are:

- o brake cost replacement
- o major overhaul of the traction motors
- o gear box replacement
- o in-shop inspection costs.

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*The base case, at its simplest, would be developed for the expected steady-state maintenance operation of the truck. The term steady-state refers to the time after the initial run-in or break-in period for all truck components has been passed. If only this steady-state case is of interest, it is generally not necessary to use the simulation cost model in its simulation mode. (A specification which refers to steady-state maintenance operation of the truck should define the time by which such operation is to occur or will be considered to have occurred.) For this base case, it might be desirable to set up the model using only the straightforward C parameter (rather than the D and E parameters). The base case would consider only scheduled or expected maintenance. This scheduled maintenance should be the same as that given in the maintenance manuals for the truck.

Consequently, brakes, motors, and gearboxes would be selected for the most stringent certification or acceptance testing. Brakes might be certified/tested for wear performance. Traction motors and gearboxes could be certified/tested for length of time between scheduled servicings and could be studied for redesign to decrease required labor. The in-shop inspection costs would generally not lead to acceptance testing or certification. However, the reduction of these costs for specific components could be considered as part of the criteria used for their acceptance.

A result of the certification and/or testing process would be to effect an increase in the quality of only the high maintenance components or assemblies. Another result would be to demonstrate that an increase in the quality of the high-maintenance-cost components or assemblies is not necessary and that their maintenance costs will actually be lower than predicted by the maintainability model.

The decision sensitivities can be considered by using a second illustrative specification. This specification requires that the maintenance methodology is used to set the minimum times for scheduled and expected maintenance operations. To do so, the simulation cost model is applied to the truck as in the previous illustration. The sensitivity analysis is used to indicate which maintenance intervals contribute strongly to costs and, consequently, are to be lengthened. The amount that these maintenance intervals are to be lengthened to produce target maintenance costs are obtained from the model.*

*The specification can require that the maintenance intervals be set to produce scheduled yearly maintenance costs which are a given fraction of the original purchase price. The specification would also have to address the costs for unscheduled maintenance (maintenance not associated with the periodic inspections). These costs must be kept low, perhaps below a certain fraction of the scheduled and expected maintenance costs. This requires that, between the scheduled and expected maintenance times, the probabilities of failure must be small.

In applying this illustrative specification, nodes 4 and 6 can be considered. At node 4, brake shoes are scrapped. The scrapping occurs because of the finite life of the shoe. This life has been taken to be 4,000 miles (about 0.025 years) for the base case. A decrease of one percent in the annual scrap flow (a decrease of 196 brake shoes) would save about $1,567. This decrease would occur if the life of the brake shoe were longer; specifically, the additional average life of the brake shoe, X, can be calculated from

$$\frac{488 \text{ shoes} \cdot 161000 \text{ miles/shoe year}}{(4000 + X) \text{ miles/shoe}} = 19589 - 196 \text{ shoes/year}$$

where the flow 19,589 shoes/year are those in the base case analysis. From this expresion, there results X = 51.4 miles/shoe. Another value for the additional average shoe life can be computed similarly. To do so, the desired annual scrap flow of brake shoes must be established from the sensitivity analysis result and from the target maintenance cost for the shoes.

The other node being considered is node 6. At this node trucks are sent to the car shop as a result of the periodic (30 day) inspections. In the base case, 672 trucks per year are sent to the car shop (see path 34 in Table 4.5a). Consequently, the base case indicates that the trucks are found to require maintenance at approximately every other inspection. The sensitivity at this node is 6421.41/% or a savings of $6,421.41 for each 6 to 7 trucks not sent each year to the car shop from the periodic inspection. For a typical truck, this represents an increase of less than one day in the average time between such servicings. In general, the number of days increase in the average time between such servicings can be computed from

$$\frac{365 \cdot \text{Number of trucks in population}}{\text{Base case annual flow on path 34}} \cdot \left[ \frac{\text{Annual dollar savings}}{\left(100 \cdot \begin{matrix}\text{Sensitivity} \\ \text{at node 6}\end{matrix}\right) - \left(\begin{matrix}\text{Annual} \\ \text{Dollar} \\ \text{Savings}\end{matrix}\right)} \right]$$

The increased average time computed from this expression is the required increase in the average maintenance-free service life of the truck. In practice, this increase can best be obtained by identifying those components which are most frequently bad-ordered during the periodic inspections. These components control the flow on path 34; therefore, increasing the average maintenance-free service life of the truck is best accomplished by giving them first consideration.

## 5.3 Simulation of Maintenance Cost Trends

The capability to simulate (or predict) truck cost and usage is a powerful feature of the SCM technique. In the present section, the simulation feature is exercised in order to illustrate this mode of SCM operation. The situation which is considered for the illustration is described in the following paragraphs.

It is desired to estimate the transient cost behavior of a new truck. When the use of this truck starts, all the components are new. As time proceeds, and the trucks age, defective units appear. These are serviced or scrapped, and reworked or new components are returned to service. As time proceeds, further additional components become defective and require replacement or service. However, the rate of increase in the flow of defective components decreases as the population becomes a mixture of newer/serviced units and older/unserviced units. Eventually a steady state situation results, in which the rate at which components become defective reaches a constant value and the associated service/replacement rate also becomes constant. At later times no changes in maintenance rates or in annual costs occur unless some change takes place in the maintenance system. Such a change could be produced by inflation, maintenance policy alterations, or differences in reliability between those components sent for maintenance or scrapping and those returned to service.

For the simulation used in the illustration below, the transient cost behavior during the time between the new truck condition and the steady state truck condition is to be estimated.* The illustration is based on the following considerations and assumptions:

- o the truck being treated is the Metroliner truck
- o the cost and operation of the Metroliner system in steady state are given by the base case analysis of Section 4.3
- o 61 cars are in the Metroliner fleet — this number of cars remains unchanged throughout the simulation (i.e., all cars are new and start service simultaneously at the start of the simulation).
- o the distribution which describes, for each component, the occurrence of defects is Weibull. (Only one defect mode exists for each component.) The parameters for this distribution and for each component have constant values.**
- o scheduled maintenance is distributed uniformly over the maintenance interval (e.g., five-year replacement of, say, secondary springs, is not made simultaneously for the whole fleet — the replacements are spread out over the five-year period.)
- o the simulation is made in terms of constant (1977) dollars.

---

*This illustration is selected because the early life of a truck is likely to be of interest to a user of the SCM in its simulation mode. In addition, requirements for simulations of early truck life costs and usage could be made part of truck specifications.

**Such a distribution can be used to represent, for a component, either "infant mortality" or "wearout behavior" — not both simultaneously.

In order to produce the simulation, data beyond those needed for the base case analysis are required. These data are

- o the two Weibull parameters for each component
- o the initial values of the state variables – population size, representative age, and quality (proportion defective) – for each component
- o the length of time for the simulation and the integration step size

and were determined as follows:

The Weibull parameters required are $\beta$ (the Weibull slope) and $\alpha$ (the characteristic life) for the defect mode associated with the component. The value of the quantity $\beta$ determines whether the component has an "infant mortality" defect behavior or a "wearout" defect behavior. Infant mortality, which occurs when $\beta < 1$, means a decrease with time of the rate at which defects occur. Wearout, which occurs when $\beta > 1$, means an increase with time of the rate at which defects occur. For the Metroliner truck, data sufficient to provide values for $\beta$ were not available. However, mechanical components typically have wearout behavior. For example, defects such as those produced by spalling, fatigue, and wear are associated with $\beta$ values of about 2 or larger. For this reason, the $\beta$ value for each component was taken to be 2.

Determination of the values for $\alpha$ was more complex. As for the $\beta$ values, sufficient data for the Metroliner truck were not available. However, this difficulty was overcome by using the assumption that, as the simulation time increases, a steady state maintenance system behavior is produced and is that given by the base case analysis of Section 4.3. Consequently, the following computations could be made:

- – In the base case analysis, the steady state representative age of each component's population was computed.
- – In the resulting base case analysis, the value of $\alpha$ for each component was then computed such that its population quality (proportion defective) would be in steady state.

The resulting values of $\alpha$ are given lines 9630 - 9632 of the Metroliner program (see Appendix A).*

The initial values of the state variables are those at which the simulation starts. Since all trucks are taken to be present and in service at this instant, the population size for each component is the same as that in the base case. However, the representative age and quality (proportion defective) for each component must be 0 at this instant.

The length of time for the simulation and the integration step size are determined by the Weibull characteristics of the components. The length of time should be longer than the characteristic life of any component in order that the entire transient can be obtained. For the simulation below, 5 years was used. The integration step size must be small in comparison to the smallest characteristic life. For the simulation below, 0.05 years was used. This step size is not smaller than the characteristic life of the brakes. Consequently, the dynamic cost behavior of the brakes was not included explicitly in the simulation (i.e., the short initial transient associated with the brakes was bypassed by constraining the rapid development of steady state brake cost and brake usage behavior).**

Results of the simulation are shown in Figures 5.2 - 5.4. Figure 5.2 gives the annual maintenance cost versus time for the Metroliner truck. The annual cost can be seen to start at $95,000 when all the trucks are new.

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*The steady state value of the representative age for each component is given in lines 9610 - 9615 of that program.

**A smaller step size could have been selected such that the dynamic cost behavior of brakes would have been obtained. However, this was not desirable because of the increase in computer time required for the simulation.

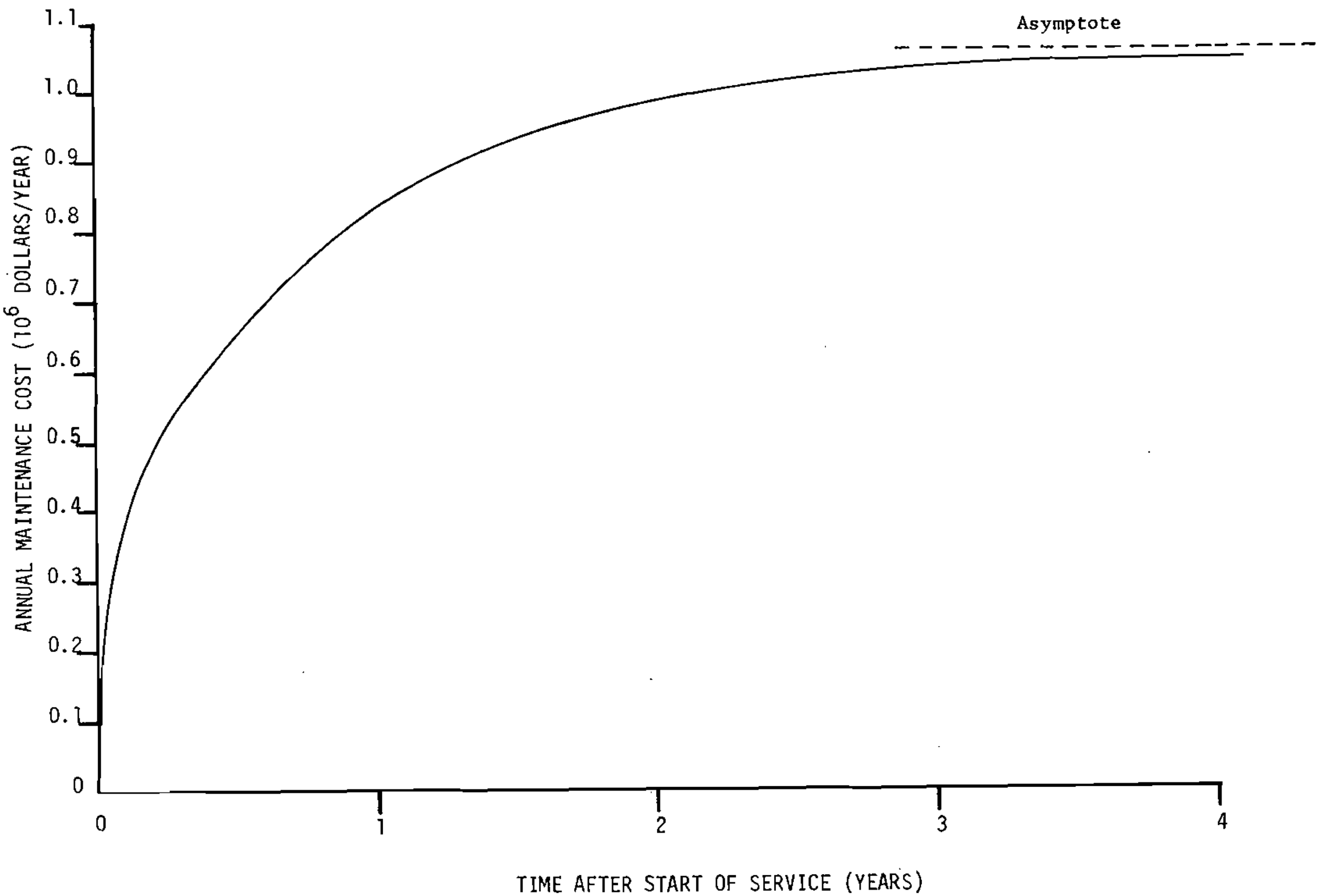


FIGURE 5.2 SIMULATION RESULTS FOR METROLINER TRUCK MAINTENANCE COSTS AND OPERATIONS

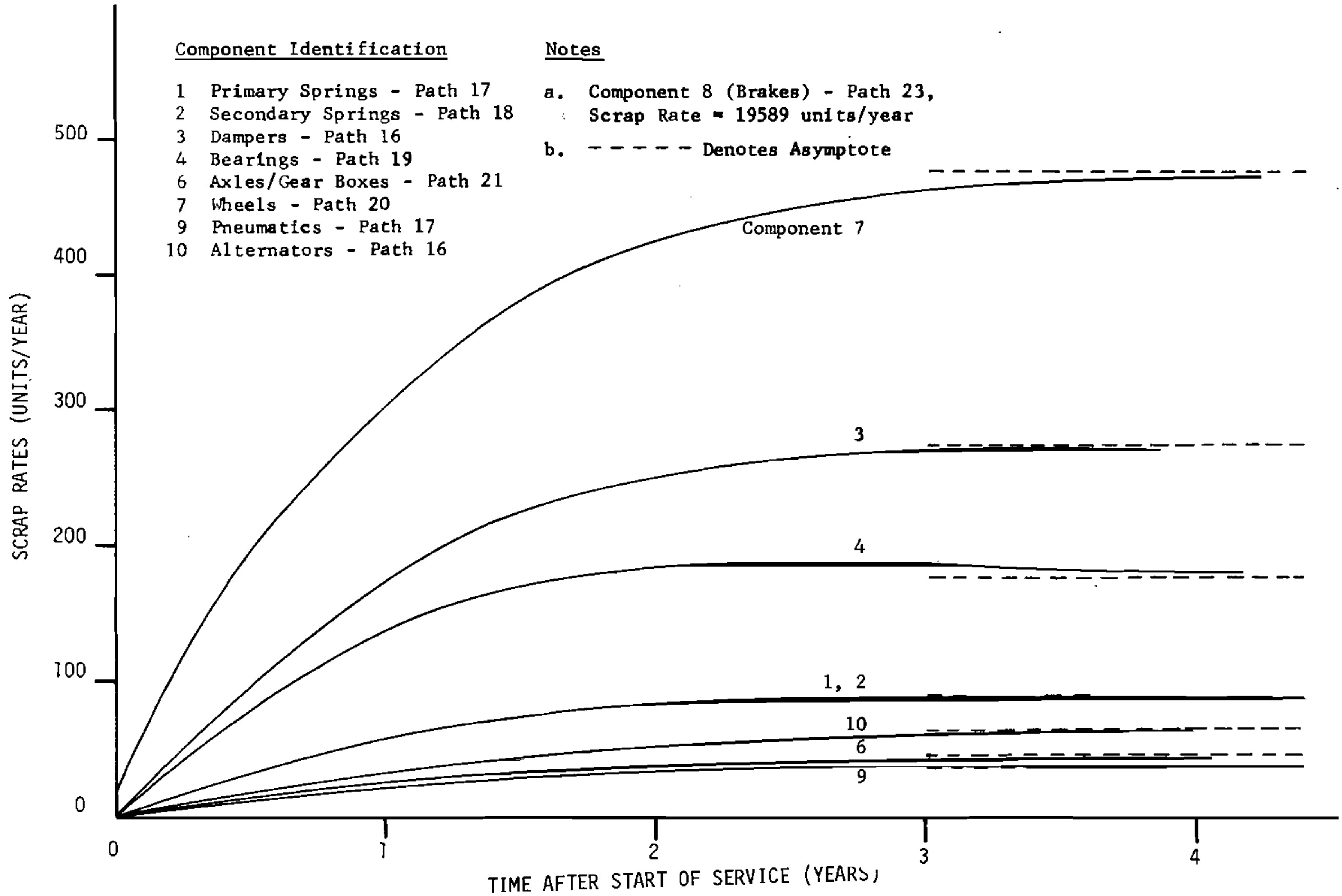


FIGURE 5.3 SIMULATION RESULTS FOR METROLINER TRUCK MAINTENANCE COSTS AND OPERATIONS

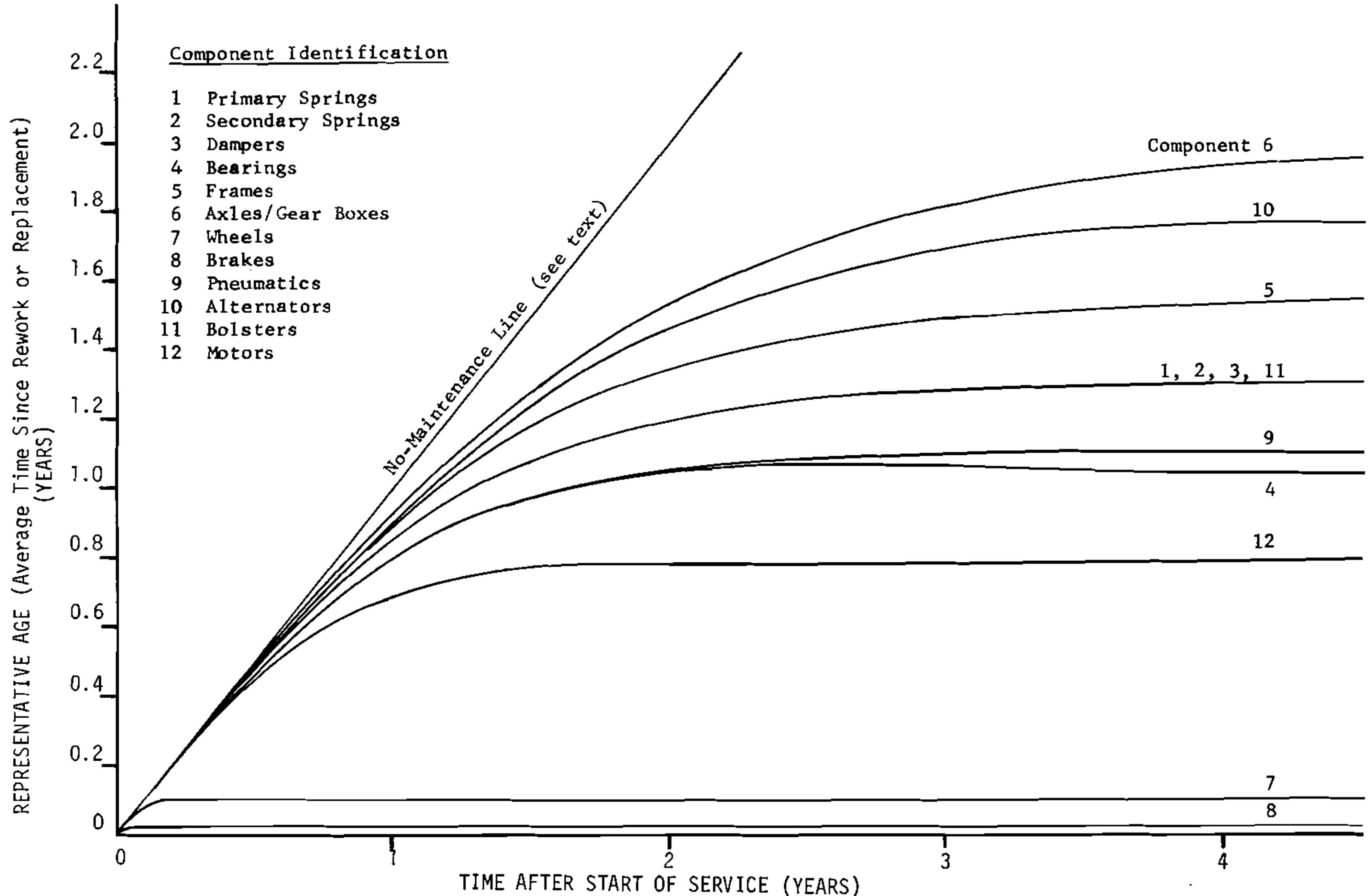


FIGURE 5.4 SIMULATION RESULTS FOR METROLINER TRUCK MAINTENANCE COSTS AND OPERATIONS

This $95,000 is composed primarily of inspection costs. As time proceeds, the annual cost rises rapidly as the costs for brake replacement reach their steady state values. Cost for other components enter the picture more slowly. After several years pass — say 4 — the maintenance system is essentially in the steady state given by the base case analysis of Section 4.3. At that time, the annual maintenance cost is about $105 million.

Figure 5.3 gives the scrap rates as a function of time. All components start (at the new truck, initial time point), with a zero scrap rate. As time progresses, the scrap rates increase gradually and, within about 4 years, approach their steady state values. Some components (e.g., 1, 2, 6, 9) tend to reach their steady state values rapidly (within about 2 years). Others (e.g., 3 and 7) take longer for this to occur. Component 4 has a scrap rate which, after about 1.7 years, is higher than that given by its asymptote.*

Figure 5.4 gives the representative age for each component as a function of time. This is not the actual age of the component -- it is the time (averaged over the component's population) measured from the time that the component was serviced (reworked or replaced). From the plot, it can be observed that component 8 reaches its steady state representative age of 0.025 years rapidly. Component 7 reaches its steady state representative age shortly thereafter, followed by components 12, 4, 9, etc. Component 6 reaches its steady state representative age most slowly, but steady state has effectively been reached within the 4.5 years covered by the plot.**

---

*The scrap rate for component 8 (brakes) is not plotted. This rate starts from zero and rapidly (within a few months) approaches its asymptotic value of 19589 units per year.

**One other line is given in Figure 5.4. This line is labelled the "no-maintenance" line. It describes the representative age behavior of a component which is never serviced (reworked or replaced). For such a component, its representative age must increase at the rate of one year per year of service life.

The illustrative results presented above can be supplemented, as desirable, by other results from the simulation. These additional results include the variation with time of all path flows, all path representative ages, all path qualities, and all path costs. In addition, cases different from the one presented can be considered. These cases could treat, for instance, the gradual introduction of the new trucks to service, the replacement of components with units having improved reliability characteristics, the variation of railroad maintenance policies with time, the effects of cost changes (including inflation), etc. It might also be desirable to consider the effects of relaxing or changing some of the considerations and assumptions given earlier in this section.

## 6. CONCLUSIONS AND RECOMMENDATIONS

### 6.1 Conclusions

The maintenance methodology for the evaluation of alternative high speed passenger train trucks has been successfully developed. In addition, the methodology -- simulation cost modelling (SCM) -- has been applied to two present-day trucks: the Metroliner truck and the Amcoach truck. These applications have indicated that:

- o the SCM technique can be applied directly to various trucks having different maintenance practices
- o the BASIC computer program for the SCM is complete, debugged, and is effectively independent of the truck being evaluated
- o data sufficient to run the SCM can be obtained
- o the base case analysis and associated sensitivity analysis can be used to identify major maintenance cost areas and components and to implement associated truck specifications
- o the simulation capability of the SCM can be employed to evaluate truck maintenance cost behavior and operation behavior which vary with time

In conducting the work, additional conclusions were reached. These are:

- o a large number of present-day and near-term trucks exist to which the SCM maintenance methodology can be applied. Such application, however, requires that the details of their maintenance practices be available and that these be cast into quantitative terms
- o the schematic diagram (which characterizes the maintenance practices of a railroad for a truck) can be constructed in large part by combining the operational framework for the railroad with the maintenance characterization for the truck.

- the schematic diagram should be constructed with and be reviewed by persons knowledgeable in the actual or planned maintenance operation

- approximate data for truck maintenance operations can readily be obtained from maintenance personnel, published literature, summaries of maintenance records, manufacturers, the FRA, and the AAR, etc. Obtaining more accurate data requires detailed review of maintenance records or gathering of maintenance data in the field

- the base case, sensitivity analyses, and other results from the SCM can be used to check errors in data entry to the computer program and to ascertain that the input data values are reasonable

- the base case, sensitivity, and other results from the SCM can indicate, quantitatively, maintenance system changes which produce target benefits established by specification

## 6.2 Recommendations

On the basis of the work performed, it is recommended that the following areas be considered for further attention:

- The usefulness and applicability of the SCM for the maintenance of high speed passenger train trucks was necessarily ascertained on the basis of a limited exposure to knowledgeable members of the industry. It is therefore suggested that this methodology be presented to and reviewed by a larger portion of the industry. Such appraisal would be valuable to determine modifications desirable in the SCM and to assess the manner in which the methodology would best be applied to general use.

- Only two trucks could be considered within the scope of the present effort. Application of the SCM to other trucks may be desirable. This would allow study of the maintenance differences among various truck types. Also, such application would indicate the desirability of modification to the maintenance methodology.

- The amount of data and accuracy of the data obtained for two trucks considered were necessarily restricted by the scope of the work. More accurate and more complete data sets should be obtained prior to any additional consideration of the maintenance costs for the two trucks.

- The number of components which were taken to comprise the trucks were also necessarily restricted by the scope of the work. It is suggested that the trucks be represented by more subassemblies and components in subsequent applications of the SCM to the two trucks. In the present application of the SCM, several assemblies were identified by the sensitivity analyses as involving relatively high maintenance costs. The more detailed representation of the trucks should therefore include treating at least these assemblies in terms of their subassemblies and/or components.

- As an alternative to treating the entire truck in terms of more components, the maintenance of each major assembly of interest could be treated separately by the SCM. In this way the need for including the maintenance details for the other assemblies in the truck would be avoided. This approach is suggested for cases where a very detailed maintenance cost evaluation for a portion of the truck is desired.

- The present application of the SCM required that each component considered possess one effective defect mode. Most components and assemblies generally have several defect modes. These defect modes can generally entail different treatment by the maintenance system. It is therefore suggested that, in the event detailed simulations are desired, the SCM be modified to allow several defect modes per component.

## APPENDIX A

### USE OF SIMULATION COST MODEL (and Auxiliary) PROGRAM AND PROGRAM LISTINGS

This section describes the manner in which the simulation cost model is employed by the user. The section indicates, with the Metroliner truck as an example, the data which the user must provide, where the data are entered into the program, and the way that the user interacts with the program. In addition, the section includes a listing of the computer program with the Metroliner data and a listing of the equivalent Amcoach data. These listings show in detail where the data are located in the program and what form the data must take. At the end of the section, a listing is also given of the auxiliary program used to compute decision parameter values from raw flow data. That listing is followed by a description of typical use of that program.

The simulation cost model and the program which computes the decision parameter values from raw flow data were developed to run on a Wang minicomputer. Accordingly, the programs are in BASIC, a widely used computer language. Because of the features of the Wang, the programs feature user-machine interaction during program execution.

It is to be noted that the minicomputer must have certain capabilities in order that the simulation cost model can be run for either the Metroliner or Amcoach trucks. These capabilities are

- 32K bytes of core memory
- floppy disc storage (of the 1023 disc sectors available, sectors 501 to 1023 are used for active memory)
- hard copy (paper) output -- not necessary but desirable.

Simulation Cost Model (Table A.1)

The data required by the program consist primarily of values for decision parameters, unit path costs, parameters indicating topology and rework locations (on the schematic diagram), and state variables.* These data requirements and the entry of the data into the program are considered next.

The decision parameter values are entered into the program in subroutine 01 (program lines 1xxx -- see program listing). To do this, the branch nodes are numbered sequentially. The data for branch node 1 (REM B 1 in the program) are placed on line 1040. Succeeding branch node decision parameter values are placed on line number y, where y is calculated from y = 1020 + 20•(branch node number). For a given branch node, data may also be entered on any line between 1020 + 20•(branch node number) and 1040 + 20•(branch node number). If data for more than 31 branch nodes are to be entered, additional line numbers 1660, 1680, etc. can be used. These additional line numbers must then also appear in line 1030 (e.g., 1030 X1 = X - 30: ON X1 GOTO 1640, 1660, 1680, etc.). After the last data value for a given branch node appears, the statement GO TO 1860 must occur.

The data for any branch node must conform to the format** shown in the following examples:

(1) A C value of 0.1234 for component 8 is entered as C(8) = 0.1234 or C(8) = 1.234E-01.

---

*The state variables are, for each component, its population size, representative age, and quality (proportion defective in the population) for the base case (reference year in a simulation).

**There are no column or spacing requirements. The statement REM xxx: indicates a remark -- the computer ignores all material between the letter M and the colon.

TABLE A.1

SCM PROGRAM LISTING WITH METROLINER DATA

```
1 DEFFN'00"LISTS"
2 REM ************************************************************ REM
4 REM *          SIMULATION COST MODEL PROGRAM                   * REM
6 REM ************************************************************ REM
8 REM * METROLINER DATA MODEL ---- LAST REVISON DATE --      2/78
10 REM *********************************************************** REM
11 REM
12 REM
15 SELECT PRINT 005(64):SELECT LIST 005(64)
20 DIM N(12),N8(12),N9(12),A(12),A8(12),A9(12),B1(12),B(12)
30 DIM R(12,3),A1(12),N1(12),Q1(12),C(12),D(12),E(12),G(12)
40 DIM Z(36),S(36),D1(36),K(36),L(36),M(36),Q(12),Q8(12),Q9(12)
50 DIM G$(72)24,C$(82)1,K$(12)1,I$2,D$1,I7$1,K7$(12)1
60 GOTO 9000
70 REM
80 REM
100 DEFFN'11(Y,W,I$)
110 Y=498+3*Y: IF Y>=501 THEN 120: STOP "SECTOR ERROR !"
120 IF I$="I" THEN 160: ON (W+1) GOTO 130,140,150
130 DATA LOAD DA T(Y,Y) N(),A(),Q(): RETURN
140 DATA LOAD DA T(Y,Y) N8(),A8(),Q8(): RETURN
150 DATA LOAD DA T(Y,Y) N9(),A9(),Q9(): RETURN
160 ON (W+1) GOTO 170,180,190
170 DATA SAVE DA T(Y,Y) N(),A(),Q(): RETURN
180 DATA SAVE DA T(Y,Y) N8(),A8(),Q8(): RETURN
190 DATA SAVE DA T(Y,Y) N9(),A9(),Q9(): RETURN
200 DEFFN'03: R6=1:IF R<>1 THEN 210:RETURN
210       FOR K=1 TO M2: IF K$(K)<>"*" THEN 230
220 R6=R6*(1-N1(K))
230       NEXT K: IF R6<>1 THEN 240: RETURN
240 R6=1-R6:Q8,X1=R6
245 IF X<>S7 THEN 250: IF K7$(K7)<>"*" THEN 250: U7=SGN(0.5+10E-
6-R6): R6=R6+U7*0.01*R6:X1=R6
250       FOR K=1 TO M2: IF K$(K)<>"*" THEN 330
260 N2=1-N1(K)+1.0E-25*SGN(-0.5+N1(K))
265 N3=N1(K)+1.0E-25*SGN(0.5-N1(K))
270 IF A1(K)<1/N3 THEN 280: A1(K)=1/N3
280 IF Q1(K)<1/N3 THEN 290: Q1(K)=1/N3
290 R6=Q8
300 A1(K)=A1(K)*N1(K)/R6+((1-N1(K)*A1(K))/N2)*(1-N1(K)/R6)
305 Q1(K)=Q1(K)*N1(K)/R6+((1-N1(K)*Q1(K))/N2)*(1-N1(K)/R6)
320 R6=X1: N1(K)=R6
330       NEXT K
340 RETURN
```

TABLE A.1 (cont.)

```
1000 DEFFN'01(X,R,S,T)
1010 IF X>30 THEN 1030
1020 ON X GOTO 1040,1060,1080,1100,1120,1140,1160,1180,1200
    ,1220,1240,1260,1280,1300,1320,1340,1360,1380,1400,1420
    ,1440,1460,1480,1500,1520,1540,1560,1580,1600,1620
1030 X1=X-30: ON X1 GOTO 1640
1040 REM B  1: C( 1)=12.0   :C9   =1                    :GOTO 1860
1060 REM B  2: C( 1)=263.3  :C9   =1                    :GOTO 1860
1080 REM B  3: C( 1)=263.3  :C9   =1                    :GOTO 1860
1100 REM B  4: C( 8)=-1.0   :D( 8)=1.00   :E( 8)=0      :GOTO 1860
1120 REM B  5: INIT(2A)K$() :MAT C=CON:MAT C=(.05)*C :GOTO 1860
1140 REM B  6: INIT(2A)K$():    MAT C=CON:MAT C=(-1.00)*C :MAT D=
CON:MAT D=(.045)*D:MAT E=CON:MAT E=(.0000005)*E       :GOTO 1860
1160 REM B  7: INIT(2A)K$():    MAT C=CON:MAT C=(-1.00)*C :MAT D=
CON:MAT D=(1.)*D:MAT E=CON:MAT E=(.87)*E              :GOTO 1860
1180 REM B  8: C( 1)=-1 :D( 1)=1.0000000   :E( 1)=.998993964
             : C( 2)=-1 :D( 2)=1.0000000   :E( 2)=.998993964
1182 REM B  8: C( 4)=-1 :D( 4)=1.0000000   :E( 4)=.99905213
1184 REM B  8: C( 5)=-1 :D( 5)=1.0000000   :E( 5)=.993011850
             : C( 6)=-1 :D( 6)=1.0000000   :E( 6)=.993009009
1186 REM B  8: C( 7)=-1 :D( 7)=1.0000000   :E( 7)=.994077830
1188 REM B  8: C( 9)=-1 :D( 9)=.35416693   :E( 9)=0
1190 REM B  8: C(11)=-1 :D(11)=1.0000000   :E(11)=.998993960
             : C(12)=-1 :D(12)=1.0000000   :E(12)=.998913043
1192 REM B  8:K$(1),K$(2),K$(4),K$(5),K$(6),K$(7),K$(8),K$(11),K
$(12)="*": GOTO 1860
1200 REM B  9: C( 3)=-1 :D( 3)=.75         :E( 3)=0
             : C(10)=-1 :D(10)=1.0         :E(10)=0
1212 REM B  9: GOTO 1860
1220 REM B 10: C( 1)=-1 :D( 1)=1.0000000   :E( 1)=.99295065
1222 REM B 10: C( 4)=-1  :D( 4)=1.0000000  :E( 4)=.99335863
1223 REM B 10: C(2),C(3),C(8),C(9),C(10),C(11)=0
1224 REM B 10: C( 5)=-1  :D( 5)=1.0000000  :E( 5)=.993076163
             : C( 6)=-1  :D( 6)=1.0000000  :E( 6)=.993062438
1226 REM B 10: C( 7)=-1  :D( 7)=1.0000000  :E( 7)=.976230780
1230 REM B 10: C(12)=-1  :D(12)=1.0000000  :E(12)=.992383025
1232 REM B 10: K$(1),K$(4),K$(5),K$(6),K$(7),K$(12)="*":
     GOTO 1860
1240 REM B 11: C( 2)=-1  :D( 2)=.25        :E( 2)=0
1242 REM B 11: C( 9)=-1  :D( 9)=1.00000    :E( 9)=0
1252 REM B 11: GOTO 1860
1260 REM B 12: C( 1)=-1  :D( 1)=1.000000000 :E( 1)=.995436105
1262 REM B 12: C( 4)=-1  :D( 4)=1.00000000  :E( 4)=.995702005
1264 REM B 12: C( 5)=-1  :D( 5)=1.000000000 :E( 5)=.996015936
```

DECISION PARAMETER VALUES

```
               : C( 6)=-1  :D( 6)=1.00000000  :E( 6)=.99593863
1266 REM B 12: C( 7)=-1  :D( 7)=1.000000000 :E( 7)=.98434774
1270 REM B 12: C(12)=-1  :D(12)=0           :E(12)=1
1272 REM B 12: K$(1),K$(4),K$(5),K$(6),K$(7)="*": GOTO 1860
1280 REM B 13: C( 4)=-1 :D( 4)=.99999999   :E( 4)=.025523344
               : C( 6)=-1 :D( 6)=.37203684   :E( 6)=.191723623
               : C( 7)=-1 :D( 7)=.99164400   :E( 7)=.240363680
1292 REM B 13: K$(4),K$(6),K$(7)="*"          :GOTO 1860
1300 REM B 14: C( 4)=-1 :D( 4)=1              :E( 4)=.0137254
               : C( 6)=-1 :D( 6)=1              :E( 6)=.000478253
               : C( 7)=.000013168
1312 REM B 14: K$(4),K$(6),K$(7)="*"          :GOTO 1860
1320 REM B 15: C( 1)=-1  :D( 1)=.250000000 :E( 1)=0
1332 REM B 15: GOTO 1860
1340 REM B 16: C(6),C(7)=1
1352 REM B 16: K$(6),K$(7)="*"  :GOTO 1860
1360 REM B 17: C( 4)=-1  :D( 4)=1.00000000  :E( 4)=0
1372 REM B 17: GOTO 1860
1380 REM B 18: C( 6)=-1  :D( 6)=1.00000000  :E( 6)=0
1392 REM B 18: GOTO 1860
1400 REM B 19: C( 7)=1
1412 REM B 19: GOTO 1860
1420 REM B 20: C( 6)=.4098360
1432 REM B 20: GOTO 1860
1440 REM B 21: C(12)=-1 :D(12)=.25             :E(12)=0
1452 REM B 21: GOTO 1860
1460 REM B 22: C( 1)=0
1472 REM B 22: GOTO 1860
1480 REM B 23: C(1)= 1                          :GOTO 1860
1500 REM B 24: C(1)= 1                          :GOTO 1860
1520 REM B 25: C(1)= 1                          :GOTO 1860
1540 REM B 26: C(1)= 1                          :GOTO 1860
1560 REM B 27: C(1)= 1                          :GOTO 1860
1580 REM B 28: C(1)= 1                          :GOTO 1860
1600 REM B 29: C(1)= 1                          :GOTO 1860
1620 REM B 30: C(1)= 1                          :GOTO 1860
1640 REM B 31: C(1)= 1                          :GOTO 1860
1860 IF C9=0 THEN 1870: C9=C(1): MAT C=CON: MAT C=(C9)*C: C9=0
1870 IF S7<=0 THEN 1920: IF X<>S7 THEN 1920: J7=J
1875 FOR Q8=1 TO M2: K7$(Q8)=K$(Q8): NEXT Q8: I7$="*": IF K7$(K7
)="*" THEN 1920
1880 IF G(K7)=0 THEN 1890: U7=1: G(K7)=G(K7)+0.01*G(K7): T7=1: I
7$="G": GOTO 1920
1890 IF C(K7)<0 THEN 1900: U7=SGN(0.5+10E-6-C(K7)): C(K7)=C(K7)+
```

V A L U E S

P A R A M E T E R

D E C I S I O N

TABLE A.1 (cont.)

```
U7*0.01*C(K7): T7=1: I7$="C": GOTO 1920
1900 IF T7=2 THEN 1910: U7=SGN(0.5+10E-6-D(K7)): D(K7)=D(K7)+U7*
0.01*D(K7): T7=2: I7$="D": GOTO 1920
1910 U7=SGN(0.5+10E-6-E(K7)): E(K7)=E(K7)+U7*0.01*E(K7): T7=1: I
7$="E"
1920        FOR K=1 TO M2
1930 IF G(K)=0 THEN 1950: N1(K)=A(K)/(2*G(K)): IF A(K)=0 THEN 19
50
1940 A1(K)=2*G(K)/A(K): Q1(K)=1: G(K)=0: GOTO 1980
1950 IF C(K)<0 THEN 1960: Q1(K)=1: N1(K)=C(K): GOTO 1980
1960 N1(K)=D(K)*Q(K)+E(K)*(1-Q(K)): IF N1(K)<>0 THEN 1970: Q1(K)
=1: GOTO 1980
1970 Q1(K)=D(K)/N1(K)
1980        NEXT K: RETURN
2000 DEFFN'02(I)
2010 IF C$(I)<>"0" THEN 2020: J=J+1: C=0: RETURN
2020 J1=I-J:J2=J1:IF J1>60 THEN 2045: IF J1>30 THEN 2040
2030 ON J1 GOTO 2050,2070,2090,2110,2130,2150,2170,2190,2210
     ,2230,2250,2270,2290,2310,2330,2350,2370,2390,2410,2430
     ,2450,2470,2490,2510,2530,2550,2570,2590,2610,2630
2040 J1=J1-30
2042 ON J1 GOTO 2650,2670,2690,2710,2730,2750,2770,2790,2810
     ,2830,2850,2870,2890,2910,2930,2950,2970,2990,3010,3030
     ,3050,3070,3090,3110,3130,3150,3170,3190,3210,3230
2045 J1=J1-60
2047 ON J1 GOTO 3250,3270,3290,3310,3330,3350,3370,3390,3410
               ,3430,3450,3470,3490,3510,3530,3550,3570
2050 REM C  1:  C( 1)=N( 1)* 000000.00          :GOTO 3900
2070 REM C  2:  C( 1)=N( 1)* 000000.00          :GOTO 3900
2090 REM C  3:  C( 1)=N( 1)* 000000.00          :GOTO 3900
2110 REM C  4:  C( 3)=N( 3)*     50.00
2111 REM C  4:  C( 8)=N( 8)* 000000.00
2112 REM C  4:  C( 9)=N( 9)*    150.00
2113 REM C  4:  C(10)=N(10)*     50.00          :GOTO 3900
2130 REM C  5:  C( 2)=N( 2)*    150.00
2131 REM C  5:  C( 9)=N( 9)*    250.00
2132 REM C  5:  C(11)=N(11)*   1000.00          :GOTO 3900
2150 REM C  6:  C( 1)=N( 1)*    200.00
2151 REM C  6:  C( 5)=N( 5)*  10000.00          :GOTO 3900
2170 REM C  7:  C( 4)=N( 4)*    150.00          :GOTO 3900
2190 REM C  8:  C( 7)=N( 7)*    200.00          :GOTO 3900
2210 REM C  9:  C( 6)=N( 6)*   2500.00          :GOTO 3900
2230 REM C 10:  C(12)=N(12)*  18000.00          :GOTO 3900
2250 REM C 11:  C( 1)=N( 1)* 000000.00          :GOTO 3900
```

PATH COSTS

```
2270 REM C 12:  C( 1)=N( 1)* 000000.00          :GOTO 3900
2290 REM C 13:  C( 1)=N( 1)* 000000.00          :GOTO 3900
2310 REM C 14:  C( 1)=N( 1)* 000000.00          :GOTO 3900
2330 REM C 15:  C( 1)=N( 1)* 000000.00          :GOTO 3900
2350 REM C 16:  C( 3)=N( 3)*     (-1.00)        :GOTO 3900
2370 REM C 17:  C( 2)=N( 2)*     (-1.00)
2371 REM C 17:  C(11)=N(11)*    (-20.00)        :GOTO 3900
2390 REM C 18:  C( 1)=N( 1)*     (-1.00)
2391 REM C 18:  C( 5)=N( 5)*   (-250.00)        :GOTO 3900
2410 REM C 19:  C( 4)=N( 4)*     (-6.00)        :GOTO 3900
2430 REM C 20:  C( 7)=N( 7)*    (-20.00)        :GOTO 3900
2450 REM C 21:  C( 6)=N( 6)*    (-25.00)        :GOTO 3900
2470 REM C 22:  C(12)=N(12)*   (-200.00)        :GOTO 3900
2490 REM C 23:  C( 8)=N( 8)*        8.00        :GOTO 3900
2510 REM C 24:  C( 1)=N( 1)* 000000.00          :GOTO 3900
2530 REM C 25:  C( 1)=N( 1)* 000000.00          :GOTO 3900
2550 REM C 26:  C( 1)=N( 1)* 000000.00          :GOTO 3900
2570 REM C 27:  C( 1)=N( 1)* 000000.00          :GOTO 3900
2590 REM C 28:  C( 1)=N( 1)* 000000.00          :GOTO 3900
2610 REM C 29:  C( 1)=N( 1)* 000000.00          :GOTO 3900
2630 REM C 30:  C( 1)=          25000.00        :GOTO 3900
2650 REM C 31:  C( 1)=N( 1)* 000000.00          :GOTO 3900
2670 REM C 32:  C( 1)=          25000.00        :GOTO 3900
2690 REM C 33:  C( 1)=N( 1)* 000000.00          :GOTO 3900
2710 REM C 34:  C( 1)=N( 1)* 000000.00          :GOTO 3900
2730 REM C 35:  C( 1)=N( 1)* 000000.00          :GOTO 3900
2750 REM C 36:  C( 1)=N( 1)*        1.44
2751 REM C 36:  C( 2)=N( 2)*         .36
2752 REM C 36:  C( 3)=N( 3)*        1.44
2753 REM C 36:  C( 4)=N( 4)*        0.00
2754 REM C 36:  C( 5)=N( 5)*        4.32
2755 REM C 36:  C( 6)=N( 6)*        0.00
2756 REM C 36:  C( 7)=N( 7)*        2.88
2757 REM C 36:  C( 8)=N( 8)*        0.00
2758 REM C 36:  C( 9)=N( 9)*        1.44
2759 REM C 36:  C(10)=N(10)*        2.30
2760 REM C 36:  C(11)=N(11)*        5.76
2761 REM C 36:  C(12)=N(12)*        0.00        :GOTO 3900
2770 REM C 37:  C( 1)=N( 1)* 000000.00          :GOTO 3900
2790 REM C 38:  C( 8)=N( 8)* 000000.00          :GOTO 3900
2810 REM C 39:  C( 1)=N( 1)* 000000.00          :GOTO 3900
2830 REM C 40:  C( 3)=N( 3)*      17.27 *Q(3)
2831 REM C 40:  C( 9)=N( 9)*     150.00 *Q(9)
2832 REM C 40:  C(10)=N(10)*     115.10 *Q(10) :GOTO 3900
```

PATH COSTS

TABLE A.1 (cont.)

```
2850 REM C 41:  C( 1)=N( 1)* 000000.00          :GOTO 3900
2870 REM C 42:  C( 5)=N( 5)*     77.72*(1-(1-Q(1))*(1-Q(2))*(1-Q
(4))*(1-Q(5))*(1-Q(6))*(1-Q(7))*(1-Q(11))*(1-Q(12)))
                                                :GOTO 3900
2890 REM C 43:  C( 2)=N( 2)*    207.24 *Q(2)
2891 REM C 43:  C( 9)=N( 9)*     60.00
2892 REM C 43:  C(11)=N(11)*    207.24 *Q(11)  :GOTO 3900
2910 REM C 44:  C( 2)=N( 2)*    103.62 *Q(2)
2911 REM C 44:  C(11)=N(11)*    100.00 *Q(11)  :GOTO 3900
2930 REM C 45:  C( 1)=N( 1)* 000000.00          :GOTO 3900
2950 REM C 46:  C( 1)=N( 1)* 000000.00          :GOTO 3900
2970 REM C 47:  C(12)=N(12)*     51.81          :GOTO 3900
2990 REM C 48:  C( 1)=N( 1)* 000000.00          :GOTO 3900
3010 REM C 49:  C( 4)=N( 4)*       .72
3011 REM C 49:  C( 6)=N( 6)*      8.64
3012 REM C 49:  C( 7)=N( 7)*      2.88          :GOTO 3900
3030 REM C 50:  C( 1)=N( 1)* 000000.00          :GOTO 3900
3050 REM C 51:  C( 1)=N( 1)* 000000.00          :GOTO 3900
3070 REM C 52:  C( 1)=N( 1)* 000000.00          :GOTO 3900
3090 REM C 53:  C( 1)=N( 1)* 000000.00          :GOTO 3900
3110 REM C 54:  C( 1)=N( 1)* 000000.00          :GOTO 3900
3130 REM C 55:  C( 1)=N( 1)* 000000.00          :GOTO 3900
3150 REM C 56:  C( 1)=N( 1)* 000000.00          :GOTO 3900
3170 REM C 57:  C( 1)=N( 1)* 000000.00          :GOTO 3900
3190 REM C 58:  C( 1)=N( 1)* 000000.00          :GOTO 3900
3210 REM C 59:  C( 1)=N( 1)* 000000.00          :GOTO 3900
3230 REM C 60:  C( 1)=N( 1)* 000000.00          :GOTO 3900
3250 REM C 61:  C( 7)=N( 7)*      6.48          :GOTO 3900
3270 REM C 62:  C( 4)=N( 4)*      4.32          :GOTO 3900
3290 REM C 63:  C( 1)=N( 1)* 000000.00          :GOTO 3900
3310 REM C 64:  C( 4)=N( 4)*     69.08          :GOTO 3900
3330 REM C 65:  C( 1)=N( 1)* 000000.00          :GOTO 3900
3350 REM C 66:  C( 7)=N( 7)*      4.32          :GOTO 3900
3370 REM C 67:  C( 1)=N( 1)* 000000.00          :GOTO 3900
3390 REM C 68:  C( 6)=N( 6)*      4.32          :GOTO 3900
3410 REM C 69:  C( 1)=N( 1)* 000000.00          :GOTO 3900
3430 REM C 70:  C( 6)=N( 6)*     17.27          :GOTO 3900
3450 REM C 71:  C( 6)=N( 6)*     89.01          :GOTO 3900
3470 REM C 72:  C( 6)=N( 6)*     17.27          :GOTO 3900
3490 REM C 73:  C( 6)=N( 6)*      4.32          :GOTO 3900
3510 REM C 74:  C( 1)=N( 1)* 000000.00          :GOTO 3900
3530 REM C 75:  C(12)=N(12)*    100.00          :GOTO 3900
3550 REM C 76:  C( 1)=N( 1)* 000000.00          :GOTO 3900
3570 REM C 77:  C(12)=N(12)*   2000.00          :GOTO 3900
```

PATH COSTS

```
3900 IF S7>=0 THEN 3920: IF J2<>(-S7) THEN 3920: J7=I
3910 C(K7)=C(K7)+0.01*ABS(C(K7))
3920 RETURN
4000 DEFFN'21: MAT K=D1: MAT Z=(T1/2)*D1: MAT Z=Z+S: RETURN
4500 DEFFN'22: MAT L=D1: MAT Z=(T1/2)*D1: MAT Z=Z+S: RETURN
5000 DEFFN'23: MAT M=D1: MAT Z=(T1)*D1: MAT Z=Z+S: RETURN
6000 DEFFN'14
6010 REM PATH 1 IDENTIFIES THE STATE VARIABLES. PATH 2 PROVIDES
     FOR EXPANSION OF EACH COMPONENT'S POPULATION
6030   FOR K=1 TO M2:              K1=-2+3*K
6040      IF Z(K1)>0 THEN 6050:    Z(K1)=0
6050      IF Z(K1+1)>0 THEN 6060: Z(K1+1)=0
6060      IF Z(K1+2)<1 THEN 6070: Z(K1+2)=1
6070      N(K)=Z(K1):A(K)=Z(K1+1):Q(K)=Z(K1+2)
6080   NEXT K
6090 GOSUB '11(1,0,"I")
6100 J=0: MAT D1=ZER
6110 J=J+1: PRINT J
6120 CONVERT STR(G$(J),1,3) TO X
6130 CONVERT STR(G$(J),4,3) TO R
6140 CONVERT STR(G$(J),7,3) TO S
6150 CONVERT STR(G$(J),10,3) TO T
6160 IF X=0 THEN 6190: IF X=-1 THEN 6730
6170 IF X>Z2 THEN 6180: GOTO 6380
6180 STOP "ERROR IN BRANCH POINT DATA"
6190 GOSUB '11(R,1,"O"): GOSUB '11(S,2,"O")
6200      FOR K=1 TO M2: K1=-2+3*K
6210 N(K)=N8(K)+N9(K): N3=N(K)+1.0E-25
6220 A(K)=(N8(K)*A8(K)+N9(K)*A9(K))/N3
6230 Q(K)=(N8(K)*Q8(K)+N9(K)*Q9(K))/N3: Q8=Q(K): A8=A(K)
6240 IF STR(G$(J),12+K,1)=" " THEN 6300
6250 CONVERT STR(G$(J),12+K,1) TO P
6260 P1=P-3: IF P1<0 THEN 6270: P=P-3: GOTO 6260
6270 A(K)=(1-Q(K))*A(K): Q(K)=ABS(R(K,P)):
     IF R(K,P)>0 THEN 6280: A(K)=0
6280 D1(K1+1)=D1(K1+1)-(A8-A(K))*N(K)/Z(K1)
6290 D1(K1+2)=D1(K1+2)-(Q8-Q(K))*N(K)/Z(K1)
6300      NEXT K
6310 GOSUB '11(T,0,"I")
6320 IF T<16 THEN 6370: IF T>27 THEN 6370
6330   FOR K=1 TO M2
6340   N8(K)=N(K): A8(K),Q8(K)=0
6350   NEXT K
6360 GOSUB '11(T-12,1,"I")
```

```
6370 GOTO 6730
6380 MAT C=ZER: MAT A1=CON: INIT(20)K$(): GOSUB '11(R,0,"O"):
     GOSUB '01(X,R,S,T)
6390 GOSUB '03: IF R<>1 THEN 6440
6400   FOR K=1 TO M2
6410   N8(K)=N1(K)*N(K): A8(K)=A1(K)*A(K): Q8(K)=Q1(K)*Q(K)
6420   NEXT K
6430 GOSUB '11(S,1,"I"): GOTO 6730
6440       FOR K=1 TO M2: K1=-2+3*K
6450 IF N1(K)>0 THEN 6460: N1(K)=0
6460 IF N1(K)<1 THEN 6470: N1(K)=1
6470 N2=1-N1(K)+1.0E-25*SGN(-.5+N1(K))
6480 N3=N1(K)+1.0E-25*SGN(+.5-N1(K))
6500 IF A1(K)<1/N3 THEN 6520: A1(K)=1/N3
6520 IF Q1(K)<1/N3 THEN 6530: Q1(K)=1/N3
6530 N8(K)=N1(K)*N(K): A8(K)=A1(K)*A(K): Q8(K)=Q1(K)*Q(K)
6540 N9(K)=N(K)-N8(K)
6550 A9(K)=(1-N1(K)*A1(K))*A(K)/N2
6560 Q9(K)=(1-N1(K)*Q1(K))*Q(K)/N2: Q8=Q8(K): Q9=Q9(K): A8=A8(K)
     : A9=A9(K)
6570 IF STR(G$(J),12+K,1)=" " THEN 6660:
     CONVERT STR(G$(J),12+K,1) TO P: P9=P
6580 P1=P9-3: IF P1<0 THEN 6590: P9=P9-3: GOTO 6580
6590 IF P<4 THEN 6630: A8(K)=(1-Q(K))*A8(K): Q8(K)=ABS(R(K,P9))
     : IF R(K,P9)>0 THEN 6600: A9(K)=0
6600 D1(K1+1)=D1(K1+1)-(A8-A8(K))*N8(K)/Z(K1)
6610 D1(K1+2)=D1(K1+2)-(Q8-Q8(K))*N8(K)/Z(K1)
6620 IF P<7 THEN 6660
6630 A9(K)=(1-Q9(K))*A9(K): Q9(K)=ABS(R(K,P9)):
     IF R(K,P9)>0 THEN 6640: A9(K)=0
6640 D1(K1+1)=D1(K1+1)-(A9-A9(K))*N9(K)/Z(K1)
6650 D1(K1+2)=D1(K1+2)-(Q9-Q9(K))*N9(K)/Z(K1)
6660       NEXT K
6670 GOSUB '11(S,1,"I"): GOSUB '11(T,2,"I")
6680 IF S<16 THEN 6730: IF S>27 THEN 6730
6690     FOR K=1 TO M2
6700     N(K)=N8(K): A(K),Q(K)=0
6710     NEXT K
6720 GOSUB '11(S-12,0,"I")
6730 IF J<>Z1 THEN 6110
6735    REM WEIBULL QUALITY DISTRIBUTION ASSUMED
6740    FOR K=1 TO M2: K1=-2+3*K
6750    GOSUB '11(2,1,"O"): GOSUB '11(3,2,"O")
6760    D1(K1)=N8(K)-N9(K):
```

```
        D1(K1+1)=D1(K1+1)+1-(N8(K)-N9(K))*Z(K1+1)/Z(K1)
6770    Q8=(B(K)/B1(K))*(Z(K1+1)/B1(K))↑(B(K)-1)
6780    D1(K1+2)=D1(K1+2)+Q8*(1-Z(K1+2))-(N8(K)-N9(K))*
        Z(K1+2)/Z(K1)
6800    NEXT K
6810      FOR I=16 TO 28: L=I: IF L<28 THEN 6820: L=3
6820       GOSUB '11(L,1,"O")
6830         FOR K=1 TO M2: K1=-2+3*K
6840         D1(K1+1)=D1(K1+1)-A8(K)*N8(K)/Z(K1)
6860         D1(K1+2)=D1(K1+2)-Q8(K)*N8(K)/Z(K1)
6870        NEXT K
6875      NEXT I
6880 RETURN
7000 DEFFN'15: SELECT PO: SELECT PRINT 005(64)
7010 IF TO<>0 THEN 7020: SELECT P2
7020 IF A=0 THEN 7030: SELECT PO: SELECT PRINT 215(132)
7030 IF A7=0 THEN 7040: SELECT PO: SELECT PRINT 005(64)
7040 PRINT :PRINT :PRINT "YEAR ";T9:PRINT
7050 GOSUB '11(1,0,"O")
7060      FOR K=1 TO M2
7070 PRINTUSING 7080,1,K,N(K),A(K),Q(K)
7080% PATH ###;  COMPONENT ##;  NUM    =##########, AV.AGE = ###
.###, QUAL = #.####
7090      NEXT K: PRINT
7100 IF A=1 THEN 7160
7110      FOR I=2 TO Z3: K1=0: GOSUB '11(I,0,"O"): FOR K=1 TO M2
: IF N(K)=0 THEN 7140
7120 PRINTUSING 7130,I,K,N(K),A(K),Q(K): K1=K1+1
7130% PATH ###;  COMPONENT ##;  NUM/YR =##########, AV.AGE = ###
.###, QUAL = #.####
7140      NEXT K: IF K1=0 THEN 7150: PRINT
7150      NEXT I
7160 J=0: CO=0: IF A=1 THEN 7180
7170 PRINT : PRINT
7180      FOR I=1 TO Z3: MAT C=ZER: GOSUB '11(I,0,"O"): K1=0: GO
SUB '02(I)
7190      FOR K=1 TO M2: CO=CO+C(K)
7200 IF A=1 THEN 7230
7210 IF C(K)=0 THEN 7230: PRINTUSING 7220,I,K,C(K): K1=K1+1
7220% PATH ###;  COMPONENT ##;   PATH COST =$#########.##
7230      NEXT K: IF K1=0 THEN 7240: PRINT
7240      NEXT I
7250 PRINT : PRINTUSING 7260,CO:PRINT
7260%                        TOTAL COST = $#########.##
```

```
7270 SELECT PO: SELECT PRINT 005(64): RETURN
8000 DEFFN'16
8010 SELECT PRINT 005(64): IF A=0 THEN 8020: SELECT PRINT 215(13
2)
8020 IF S7<>0 THEN 8030: S7=V7+1: V7=S7:K7=1 : P7=0: C7=C0: PRIN
T : RETURN
8030 IF S7<0 THEN 8110: R7=(C0-C7)/U7
8040 PRINTUSING 8050,S7,J7,K7,R7,I7$: P7=P7+1
8050% BRANCH NODE ###,  NODE ###,  COMPONENT ##,  SENSITIVITY =
$#############.##/%,    #
8060 IF T7<>2 THEN 8070: RETURN
8070 K7=K7+1: IF K7>M2 THEN 8080:Q8=1:IF K7$(K7)="*" THEN 8075:
RETURN
8075 IF K7$(Q8)="*" THEN 8070:Q8=Q8+1:IF Q8<K7 THEN 8075:RETURN

8080 INIT(20)K7$(): IF P7=0 THEN 8090: PRINT : P7=0
8090 S7=S7+1:K7=1: IF S7>Z2 THEN 8100: RETURN
8100 PRINT : PRINT : S7=-1: K7=1: P7=0: RETURN
8110 R7=(C0-C7)/1.0: IF R7=0 THEN 8130:
     PRINTUSING 8120,-S7,J7,K7,R7: P7=P7+1
8120%   COST PATH ###,  PATH ###,  COMPONENT ##,  SENSITIVITY =
$#############.##/%
8130 K7=K7+1: IF K7>M2 THEN 8140: RETURN
8140 IF P7=0 THEN 8150: PRINT : P7=0
8150 S7=S7-1: K7=1: IF S7<-Z4 THEN 8160: RETURN
8160 S7=0: T9=T0: PRINT : RETURN
9000 INIT(20) G$(),K7$(): INIT(30) C$(): S7,C9=0: T7,K7=1:
     MAT G=ZER
9010 READ M2: DATA 12: REM --- M2 IS THE NUMBER OF COMPONENTS
9020 READ Z1: DATA 72: REM --- Z1 IS THE NUMBER OF NODE POINTS
                                (BRANCH & SUM & EXTRAS)
9030 READ Z2: DATA 22:REM --- Z2 IS THE NUMBER OF BRANCH POINTS
9040 READ Z3: DATA 81: REM --- Z3 IS THE TOTAL NUMBER OF PATHS
9050 READ Z4: DATA 81: REM --- Z4 IS THE NUMBER OF PATHS WITH
                                ASSOCIATED COST
9060 REM PATH Z3+1 IS 'DUMPING GROUND' FOR MANY OF THE FLOWS
     BACK TO THE 'FIELD'
9070 MAT REDIM G$(Z1)24,C$(Z3)1,K$(M2)1,K7$(M2)1
9080       FOR I=1 TO Z1
9090 READ G1: CONVERT G1 TO STR(G$(I),1,3),(-##)
9100 REM THIS PART OF G$() IDENTIFIES THE BRANCH-SUMMATION-
     EXTRA NODES. BRANCH NODES ARE SEQUENTIAL NUMBERS, SUM-
     MATION NODES (0), EXTRA NODES (-1).
9120 DATA  1, 2, 3, 4, 0,   5, 6, 0,-1, 7,   8, 9, 0,10,11,
```

SIZE OF MODEL

```
                0,-1,-1,-1,12,  -1,13,14,15,-1,  -1,-1,-1, 0,16,
                17, 0,18,19, 0,  20, 0, 0, 0, 0
9122 DATA -1,-1,-1,-1,-1,  -1,-1,-1,-1,21,  22,-1,-1,-1,-1,
                -1, 0, 0,-1, 0,   0,-1,-1,-1, 0,   0, 0,-1,-1, 0,
                -1,-1
9130        NEXT I
9140        FOR I=1 TO Z1
9150 READ G1,G2,G3: IF G3<>1 THEN 9160: G3=Z3+1
9160 CONVERT G1 TO STR(G$(I),4,3),(###)
9170 CONVERT G2 TO STR(G$(I),7,3),(###)
9180 CONVERT G3 TO STR(G$(I),10,3),(###)
9190 REM --------- G$() DEFINED AS FOLLOWS
9191 REM --------- FOR  SUMMATION NODES  --- 1ST # = FROM PATH
9193 REM ---------------------------------- 2ND # = FROM PATH
9194 REM ---------------------------------- 3RD # =   TO PATH
9200 REM --------- FOR BRANCH NODES -------- 1ST # = FROM PATH
9212 REM ---------------------------------- 2ND # =   TO BAD
9214 REM ---------------------------------- 3RD # =   TO GOOD
9230 DATA  1,32, 1,    1,30, 1,     1,79, 1,
          79,23,80,  80,11,81,    32,34,33
9232 DATA 30,35,31,   35,34,36,     0, 0, 0,
          36,37,38,   37,42,39,    39,16,40
9234 DATA 40, 4,41,   42,46,43,    43,17,44,
          44, 5,45,    0, 0, 0,     0, 0, 0
9236 DATA  0, 0, 0,   46,48,47,     0, 0, 0,
          48,49,50,   49,62,61,    50,18,51
9238 DATA  0, 0, 0,    0, 0, 0,     0, 0, 0,
           0, 0, 0,   51, 6,52,    62,66,63
9240 DATA 63,19,64,   64, 7,65,    66,70,67,
          67,20,68,   68, 8,69,    70,21,71
9242 DATA 71, 9,72,   72,69,73,    73,65,74,
          74,61,53,    0, 0, 0,     0, 0, 0
9244 DATA  0, 0, 0,    0, 0, 0,     0, 0, 0,
           0, 0, 0,    0, 0, 0,     0, 0, 0
9246 DATA  0, 0, 0,   47,76,75,    76,22,77,
           0, 0, 0,    0, 0, 0,     0, 0, 0
9248 DATA  0, 0, 0,    0, 0, 0,    77,10,78,
          78,75,55,    0, 0, 0,    53,52,54
9250 DATA 55,54,56,    0, 0, 0,     0, 0, 0,
           0, 0, 0,   56,45,57,    57,41,58
9260 DATA 58,38,59,    0, 0, 0,     0, 0, 0,
           2,59,60,    0, 0, 0,     0, 0, 0
9270        NEXT I
9280 REM THE 12 PATHS 16-27 ARE RESERVED FOR SCRAP YARD PATHS.
```

IDENTIFICATION OF BRANCH, SUMMATION, AND EXTRA NODES

TOPOLOGY OF SCHEMATIC DIAGRAM

```
     THE FLOWS IN PATHS 16-27 ARE COMPENSATED BY MANUFACTUR
     ERS' FLOWS IN PATHS 4-15,PATH 3 IS NON-COMPSATED SCRAP
9310 READ R: DATA 14   TOTAL NUMBER OF REWORKINGS
9320      FOR J=1 TO R
9330 READ K,I,A,I$,R(K,I)
9331 DATA 8,  1,   4,  "GD",  0
9332 DATA 3,  1,  12,  "GD",  0,  9,  1,  12,  "GD",  0
9333 DATA 10, 1,  12,  "GD",  0,  2,  1,  15,  "GD",  0
9334 DATA 11, 1,  15,  "GD",  0, 12,  1,  50,  "GD",  0
9335 DATA 12, 2,  51,  "GD",  0,  1,  1,  24,  "GD",  0
9336 DATA 5,  1,  24,  "GD",  0,  7,  1,  23,  "GA",  0
9337 DATA 4,  1,  31,  "GA",  0,  7,  2,  34,  "GD",  0
9338 DATA 6,  1,  36,  "GD",  0
                                                REWORK DETAILS
9340 REM --- IF G$() IS NOT BLANK HERE THEN THE REFERENCED
     REM --- COMPONENT K HAS ITS I-TH REWORK ON A PATH FROM
     REM --- NODE A.
9350 REM --- I$ IDENTIFIES REWORK IN PATHS GOOD "G", BAD "B",
     REM --- OR ALL "A" ON DEFECTIVES "D" OR ALL "A" UNITS.
9360 REM --- COMPONENT QUALITY AFTER REWORK IS R(K,I).THE TOTAL
     REM --- NUMBER OF REWORKINGS FOR ALL THE COMPONENTS IS R
9365 R(K,I)=R(K,I)+1.0E-25: IF STR(I$,2,1)="D" THEN 9370:
     R(K,I)=-R(K,I)
9370 IF STR(I$,1,1)="G" THEN 9380: I=I+3:
     IF STR(I$,1,1)="B" THEN 9380: I=I+3
9380 CONVERT I TO I$,(##): STR(G$(A),12+K,1)=STR(I$,2,1)
9390      NEXT J
9395 REM
9397 REM
9400 INPUT "DO YOU WANT TOPOLOGY PRINTOUT (1 OR 0)",A
9410 IF A=0 THEN 9460: SELECT PRINT 215(132)
9420      FOR I=1 TO Z1
9430 PRINTUSING 9440,I,STR(G$(I),1,3),STR(G$(I),4,3),STR(G$(I),7
,3),STR(G$(I),10,3),STR(G$(I),13,12)
9440%NODE ###;    BN=###    FP=###    BP/FP=###    GP/TP=###    #
###########
9450      NEXT I: SELECT PRINT  005(64)
9460      FOR I=1 TO Z3
9470 READ A: CONVERT A TO C$(I),(#)
9480 REM C$() IDENTIFIES PATHS HAVING ANY ASSOCIATED COSTS
9490      NEXT I
9500 DATA 1,1,1,1,1, 1,1,1,1,1, 1,1,1,1,1, 1,1,1,1,1, 1,1,1,1,1
     , 1,1,1,1,1, 1,1,1,1,1, 1,1,1,1,1, 1,1,1,1,1, 1,1,1,1,1
9510 DATA 1,1,1,1,1, 1,1,1,1,1, 1,1,1,1,1, 1,1,1,1,1, 1,1,1,1,1
     , 1,1,1,1,1, 1
                                                IDENTI-
                                                FICATION
                                                OF COST
                                                PATHS
```

```
9530 INPUT "SENSITIVITY ANALYSIS (1 OR 0)",A7:
     IF A7=0 THEN 9540
9535 INPUT "SENS. ANAL. TO START AT (1 TO Z2 FOR BRANCH NODES, -
1 TO -Z4 FOR COST PATHS)",V7: V7=V7-1
9540 INPUT "HARD COPY (0, 1, OR 2)",A
9550 INPUT "DISK TO BE USED (F OR R)",D$
9560 IF D$<>"F" THEN 9570: SELECT DISK 310: GOTO 9580
9570 IF D$<>"R" THEN 9550: SELECT DISK B10
9580 M1=3*M2
9590 MAT REDIM N(M2),A(M2),Q(M2),N8(M2),A8(M2),Q8(M2),N9(M2),
     A9(M2),Q9(M2),R(M2,3),Z(M1),S(M1),D1(M1),K(M1),L(M1),M(M1)
9600 MAT REDIM A1(M2),N1(M2),Q1(M2),C(M2),D(M2),E(M2),G(M2),B(M2
),B1(M2)
9610 MAT READ Z: DATA  488,1.3138,.0299313, 488,1.3138,.0299313
9611             DATA  488,1.3138,.0299313, 488,1.0170,.0145307
9612             DATA  122,1.5517,.0252918, 244,1.9975,.025803
9613             DATA  488,0.1004,.3062709, 488,0.0249,.152459
9614             DATA  122,1.1038,.0357143, 122,1.8009,.0217597
9615             DATA  122,1.3138,.0299313, 244,0.7949,.0498982
9620        FOR K=1 TO M2: READ N(K),B(K),B1(K)
9630 DATA 0,2,1.82998, 0,2,1.82998, 0,2,1.82998, 0,2,2.32138
9631 DATA 0,2,2.16651, 0,2,2.78818, 0,2,0.14307, 0,2,0.03243
9632 DATA 0,2,1.53289, 0,2,2.51896, 0,2,1.82998, 0,2,1.09577
9640 REM FOR COMPONENT K, N(K) IS ITS RATE OF POPULATION
     EXPANSION, B(K) IS ITS WEIBULL SLOPE, AND B1(K) IS ITS
     CHARACTERISTIC LIFE.
9650        NEXT K
9660 MAT A=ZER: MAT Q=ZER: GOSUB '11(2,0,"I")
9670 MAT N=ZER: FOR I=3 TO Z3: GOSUB '11(I,0,"I"): NEXT I
9680 READ T0,T1,T2: DATA  0,1,1  SIMULATION CONTROL
9690 T9=0: I9=T2: GOTO 9770
9692 REM
9694 REM
9696 REM
9700 REM ------------------ START OF COMPUTATION ------------------
9710 GOSUB '14: MAT S=Z: IF I9>0 THEN 9720: GOSUB '15
9720 IF A7=0 THEN 9730: GOSUB '16: SELECT PRINT 005(64):
     IF T9=0 THEN 9710
9730 IF T9<T0 THEN 9740: END
9740 GOSUB '21: T9=T9+T1/2: GOSUB '14: GOSUB '22
9750 GOSUB '14: GOSUB '23: T9=T9+T1/2: GOSUB '14
9760 FOR I=1TO M1:Z(I)=S(I)+T1*(K(I)+2*L(I)+2*M(I)+D1(I))/6:
     NEXT I
9770 I9=I9+1: IF I9<T2 THEN 9710: I9=0: GOTO 9710
9999 REM ------------------ LAST LINE ------------------
```

BASE CASE VALUES OF STATE VARIABLES

EXPANSION RATES & WEIBULL PARAMETER VALUES

TABLE A.2

AMCOACH DATA LISTING

```
1 DEFFN'00"LISTS"
2 REM ***********************************************************
3 REM *   AMFLEET COST MODEL  "221"  AMCOACH DISK            REM
4 REM ***********************************************************
8 REM *   AMFLEET DATA ONLY ---- LAST REVISION DATE ---- 12/77
10 REM **********************************************************
11 REM
12 REM
15 SELECT PRINT 005(64):SELECT LIST 005(64)
1040 REM  N 1: C( 1)=12           :C9   =1
1052           GOTO 1860
1080 REM  N 2: C( 1)=365          :C9   =1
1092           GOTO 1860
1100 REM  N 6: C( 1)=-1 :D( 1)=1.0000000  :E( 1)=.08975936
             : C( 2)=-1 :D( 2)=1.0000000  :E( 2)=.05003181
1102 REM  N 6: C( 3)=-1 :D( 3)=1          :E( 3)=.08448446
             : C( 4)=-1 :D( 4)=1          :E( 4)=.08593090
1104 REM  N 6: C( 5)=-1 :D( 5)=1          :E( 5)=.092210499
             : C( 6)=-1 :D( 6)=1          :E( 6)=.089759363
1106 REM  N 6: C( 7)=-1 :D( 7)=1          :E( 7)=.070309693
             : C( 8)=-1 :D( 8)=1          :E( 8)=.011151879
1108 REM  N 6: C( 9)=-1 :D( 9)=1          :E( 9)=.089740011
             : C(10)=-1 :D(10)=1          :E(10)=.089740011
1110 REM  N 6: C(11)=-1 :D(11)=1          :E(11)=.054145273
             : C(12)=-1 :D(12)=0          :E(12)=0
1112           INIT(2A)K$(): K$(12)=" "   :
               GOTO 1860
1120 REM  N 7: C( 1)=-1 :D( 1)=.020330756 :E( 1)=.008226702
             : C( 2)=-1 :D( 2)=.02057592  :E( 2)=.007686686
1122 REM  N 7: C( 3)=-1 :D( 3)=.020510053 :E( 3)=.0081548016
             : C( 4)=-1 :D( 4)=.020420290 :E( 4)=.0081750777
1124 REM  N 7: C( 5)=-1 :D( 5)=.020512936 :E( 5)=.008259063
             : C( 6)=-1 :D( 6)=.020330892 :E( 6)=.008226739
1126 REM  N 7: C( 7)=-1 :D( 7)=.020479549 :E( 7)=.007964289
             : C( 8)=-1 :D( 8)=.020509663 :E( 8)=.0071651838
1128 REM  N 7: C( 9)=-1 :D( 9)=.019789633 :E( 9)=.0082287605
             : C(10)=-1 :D(10)=.019789633 :E(10)=.0082287605
1130 REM  N 7: C(11)=-1 :D(11)=.020509761 :E(11)=.0077453750
             : C(12)=-1 :D(12)=0          :E(12)=0
1132           INIT(2A)K$(): K$(12)=" "   :
               GOTO 1860
1140 REM  N10: C( 1)=-1 :D( 1)=.000001675 :E( 1)=.000001675
             : C( 2)=-1 :D( 2)=.090993939 :E( 2)=0
1142 REM  N10: C( 3)=-1 :D( 3)=0          :E( 3)=0
```

```
                 : C( 4)=-1 :D( 4)=.00001       :E( 4)=.00001
1144 REM   N10: C( 5)=-1 :D( 5)=.9357196    :E( 5)=0
                 : C( 6)=-1 :D( 6)=.00001       :E( 6)=.00001
1146 REM   N10: C( 7)=-1 :D( 7)=.116649     :E( 7)=.00153162
                 : C( 8)=-1 :D( 8)=1            :E( 8)=1
1148 REM   N10: C( 9)=-1 :D( 9)=0           :E( 9)=0
                 : C(10)=-1 :D(10)=1            :E(10)=1
1150 REM   N10: C(11)=-1 :D(11)=0           :E(11)=0
                 : C(12)=-1 :D(12)=0            :E(12)=0
1152              K$(1),K$(4),K$(6),K$(7)="*" :
                  GOTO 1860
1160 REM   N11: C( 1)=-1 :D( 1)=1.0000000  :E( 1)=0
                 : C( 2)=-1 :D( 2)=0            :E( 2)=0
1162 REM   N11: C( 3)=-1 :D( 3)=0           :E( 3)=0
                 : C( 4)=-1 :D( 4)=1            :E( 4)=0
1164 REM   N11: C( 5)=-1 :D( 5)=0           :E( 5)=0
                 : C( 6)=-1 :D( 6)=1            :E( 6)=1
1166 REM   N11: C( 7)=-1 :D( 7)=1           :E( 7)=1
                 : C( 8)=-1 :D( 8)=0            :E( 8)=0
1168 REM   N11: C( 9)=-1 :D( 9)=0           :E( 9)=0
                 : C(10)=-1 :D(10)=0            :E(10)=0
1170 REM   N11: C(11)=-1 :D(11)=0           :E(11)=0
                 : C(12)=-1 :D(12)=0            :E(12)=0
1172              K$(1),K$(4),K$(6),K$(7)="*" :
                  GOTO 1860
1180 REM   N12: MAT C=CON :MAT C=(-1)*C  :MAT D=CON   :MAT E=ZER
                 : E(6)=1     :E(7)=1
1192              GOTO 1860
1200 REM   N15: MAT C=CON :MAT C=(-1)*C  :MAT D=CON   :MAT E=ZER
                 : E(6)=1     :E(7)=1
1212              K$(1),K$(4),K$(6),K$(7)="*" :
                  GOTO 1860
2050 REM C   1:  C( 1)=N( 1)* 000000.00          :GOTO 3900
2070 REM C   2:  C( 1)=N( 1)* 000000.00          :GOTO 3900
2090 REM C   3:  C( 1)=N( 1)* 000000.00          :GOTO 3900
2110 REM C   4:  C( 2)=N( 2)*    400.00
2111 REM C   4:  C( 5)=N( 5)*      2.00
2112 REM C   4:  C( 8)=N( 8)*     42.00
2113 REM C   4:  C(10)=N(10)*     50.00          :GOTO 3900
2130 REM C   5:  C( 1)=N( 1)*     40.00
2131 REM C   5:  C( 4)=N( 4)*     75.00
2132 REM C   5:  C( 6)=N( 6)*    400.00
2133 REM C   5:  C( 7)=N( 7)*    200.00          :GOTO 3900
2150 REM C   6:  C( 1)=N( 1)* 000000.00          :GOTO 3900
```

```
2170 REM C  7:  C( 1)=N( 1)* 000000.00        :GOTO 3900
2190 REM C  8:  C( 1)=N( 1)* 000000.00        :GOTO 3900
2210 REM C  9:  C( 1)=N( 1)* 000000.00        :GOTO 3900
2230 REM C 10:  C( 1)=N( 1)* 000000.00        :GOTO 3900
2250 REM C 11:  C( 1)=N( 1)* 000000.00        :GOTO 3900
2270 REM C 12:  C( 1)=N( 1)* 000000.00        :GOTO 3900
2290 REM C 13:  C( 1)=N( 1)* 000000.00        :GOTO 3900
2310 REM C 14:  C( 1)=N( 1)* 000000.00        :GOTO 3900
2330 REM C 15:  C( 1)=N( 1)* 000000.00        :GOTO 3900
2350 REM C 16:  C( 1)=N( 1)* 000000.00        :GOTO 3900
2370 REM C 17:  C( 4)=N( 4)*    (-6.00)
2371 REM C 17:  C( 6)=N( 6)*    (-1.00)
2372 REM C 17:  C( 7)=N( 7)*   (-20.00)       :GOTO 3900
2390 REM C 18:  C( 1)=N( 1)* 000000.00        :GOTO 3900
2410 REM C 19:  C( 1)=N( 1)* 000000.00        :GOTO 3900
2430 REM C 20:  C( 1)=N( 1)* 000000.00        :GOTO 3900
2450 REM C 21:  C( 1)=N( 1)* 000000.00        :GOTO 3900
2470 REM C 22:  C( 1)=N( 1)* 000000.00        :GOTO 3900
2490 REM C 23:  C( 1)=N( 1)* 000000.00        :GOTO 3900
2510 REM C 24:  C( 1)=N( 1)* 000000.00        :GOTO 3900
2530 REM C 25:  C( 1)=N( 1)* 000000.00        :GOTO 3900
2550 REM C 26:  C( 1)=N( 1)* 000000.00        :GOTO 3900
2570 REM C 27:  C( 1)=N( 1)* 000000.00        :GOTO 3900
2590 REM C 28:  C( 1)=N( 1)* 000000.00        :GOTO 3900
2610 REM C 29:  C( 1)=N( 1)* 000000.00        :GOTO 3900
2630 REM C 30:  C( 2)=N( 2)*        .12
2631 REM C 30:  C( 5)=N( 5)*        .024
2632 REM C 30:  C( 7)=N( 7)*        .0966
2633 REM C 30:  C( 8)=N( 8)*        .0966     :GOTO 3900
2650 REM C 31:  C( 1)=N( 1)* 000000.00        :GOTO 3900
2670 REM C 32:  C( 2)=N( 2)*        .96
2671 REM C 32:  C( 5)=N( 5)*        .60
2672 REM C 32:  C( 7)=N( 7)*        .54
2673 REM C 32:  C( 8)=N( 8)*        .56
2674 REM C 32:  C( 9)=N( 9)*        .18       :GOTO 3900
2690 REM C 33:  C( 1)=N( 1)* 000000.00        :GOTO 3900
2710 REM C 34:  C( 1)=N( 1)* 000000.00        :GOTO 3900
2730 REM C 35:  C( 1)=N( 1)* 000000.00        :GOTO 3900
2750 REM C 36:  C( 1)=N( 1)* 000000.00        :GOTO 3900
2770 REM C 37:  C( 1)=N( 1)* 000000.00        :GOTO 3900
2790 REM C 38:  C( 2)=N( 2)*      8.64*Q(2)
2791 REM C 38:  C( 3)=N( 3)*      2.16*Q(3)
2792 REM C 38:  C( 4)=N( 4)*      2.88*Q(4)
2793 REM C 38:  C( 5)=N( 5)*     25.90*Q(5)
```

TABLE A.2 (cont.)

```
2794 REM C 38:  C( 7)=N( 7)*     12.95*Q(7)
2795 REM C 38:  C( 9)=N( 9)*      8.64*Q(9)
2796 REM C 38:  C(11)=N(11)*     17.27*Q(11)     :GOTO 3900
2810 REM C 39:  C( 2)=N( 2)*    276.32*Q(2)
2811 REM C 39:  C( 5)=N( 5)*     34.50*Q(5)
2812 REM C 39:  C( 8)=N( 8)*     37.30*Q(8)
2813 REM C 39:  C(10)=N(10)*     11.31*Q(10)    :GOTO 3900
2830 REM C 40:  C( 1)=N( 1)* 00000.00           :GOTO 3900
2850 REM C 41:  C( 1)=N( 1)* 000000.00          :GOTO 3900
2870 REM C 42:  C( 7)=N( 7)*     51.81           :GOTO 3900
2890 REM C 43:  C( 1)=N( 1)* 000000.00           :GOTO 3900
2910 REM C 44:  C( 1)=N( 1)* 000000.00         :GOTO 3900
2930 REM C 45:  C( 1)=N( 1)* 000000.00         :GOTO 3900
2950 REM C 46:  C( 1)=N( 1)* 000000.00         :GOTO 3900
2970 REM C 47:  C( 1)=N( 1)* 000000.00         :GOTO 3900
2990 REM C 48:  C( 1)=N( 1)* 000000.00         :GOTO 3900
3010 REM C 49:  C( 1)=N( 1)* 000000.00         :GOTO 3900
3030 REM C 50:  C( 1)=N( 1)* 000000.00         :GOTO 3900
3050 REM C 51:  C( 1)=N( 1)* 000000.00         :GOTO 3900
3070 REM C 52:  C( 1)=N( 1)* 000000.00         :GOTO 3900
3090 REM C 53:  C( 1)=N( 1)* 000000.00         :GOTO 3900
3110 REM C 54:  C( 1)=N( 1)* 000000.00         :GOTO 3900
3130 REM C 55:  C( 1)=N( 1)* 000000.00         :GOTO 3900
3150 REM C 56:  C( 1)=N( 1)* 000000.00         :GOTO 3900
3170 REM C 57:  C( 1)=N( 1)* 000000.00         :GOTO 3900
3190 REM C 58:  C( 1)=N( 1)* 000000.00         :GOTO 3900
3210 REM C 59:  C( 1)=N( 1)* 000000.00         :GOTO 3900
3230 REM C 60:  C( 1)=N( 1)* 000000.00         :GOTO 3900
3250 REM C 61:  C( 7)=N( 7)* 000000.00         :GOTO 3900
3270 REM C 62:  C( 4)=N( 4)* 000000.00         :GOTO 3900
3290 REM C 63:  C( 1)=N( 1)* 000000.00         :GOTO 3900
3310 REM C 64:  C( 1)=N( 1)* 000000.00         :GOTO 3900
3330 REM C 65:  C( 1)=N( 1)* 000000.00         :GOTO 3900
3350 REM C 66:  C( 1)=N( 1)* 000000.00         :GOTO 3900
3370 REM C 67:  C( 1)=N( 1)* 000000.00         :GOTO 3900
3390 REM C 68:  C( 1)=N( 1)* 000000.00         :GOTO 3900
3410 REM C 69:  C( 1)=N( 1)* 000000.00         :GOTO 3900
3430 REM C 70:  C( 1)=N( 1)* 000000.00         :GOTO 3900
3450 REM C 71:  C( 1)=N( 1)* 000000.00         :GOTO 3900
3470 REM C 72:  C( 1)=N( 1)* 000000.00         :GOTO 3900
3490 REM C 73:  C( 1)=N( 1)* 000000.00         :GOTO 3900
3510 REM C 74:  C( 1)=N( 1)* 000000.00         :GOTO 3900
3530 REM C 75:  C( 1)=N( 1)* 000000.00         :GOTO 3900
3550 REM C 76:  C( 1)=N( 1)* 000000.00         :GOTO 3900
```

TABLE A.2 (cont.)

```
3570 REM C 77:  C( 1)=N( 1)* 000000.00         :GOTO 3900
9010 READ M2: DATA 12: REM *** M2 IS THE NUMBER OF COMPONENTS
9020 READ Z1: DATA 72: REM *** Z1 IS THE NUMBER OF NODE POINTS
                               (BRANCH & SUM & EXTRAS)
9030 READ Z2: DATA  8: REM *** Z2 IS THE NUMBER OF BRANCH POINTS

9040 READ Z3: DATA 81: REM *** Z3 IS THE TOTAL NUMBER OF PATHS
9050 READ Z4: DATA 81: REM *** Z4 IS THE NUMBER OF PATHS WITH
                               ASSOCIATED COST
9120 DATA  1, 2,-1,-1,-1,   3, 4, 0,-1, 5,   6, 7, 0,-1, 8,
           0,-1,-1,-1,-1,  -1,-1,-1,-1,-1,  -1,-1,-1,-1,-1,
          -1,-1,-1,-1,-1,  -1,-1,-1,-1,-1
9122 DATA -1,-1,-1,-1,-1,  -1,-1,-1,-1,-1,  -1,-1,-1,-1,-1,
          -1,-1,-1,-1,-1,  -1,-1,-1,-1,-1,   0, 0,-1,-1, 0,
          -1,-1
9230 DATA  1,32, 1,    1,30, 1,     0, 0, 0,     0, 0, 0,
           0, 0, 0,   32,34,33
9232 DATA 30,35,31,   35,34,36,     0, 0, 0,    36,37,38,
          37,42,39,   39,16,40
9234 DATA 40, 4,41,    0, 0, 0,    42,17,44,    44, 5,45,
           0, 0, 0,    0, 0, 0
9236 DATA  0, 0, 0,    0, 0, 0,     0, 0, 0,     0, 0, 0,
           0, 0, 0,    0, 0, 0
9238 DATA  0, 0, 0,    0, 0, 0,     0, 0, 0,     0, 0, 0,
           0, 0, 0,    0, 0, 0
9240 DATA  0, 0, 0,    0, 0, 0,     0, 0, 0,     0, 0, 0,
           0, 0, 0,    0, 0, 0
9242 DATA  0, 0, 0,    0, 0, 0,     0, 0, 0,     0, 0, 0,
           0, 0, 0,    0, 0, 0
9244 DATA  0, 0, 0,    0, 0, 0,     0, 0, 0,     0, 0, 0,
           0, 0, 0,    0, 0, 0
9246 DATA  0, 0, 0,    0, 0, 0,     0, 0, 0,     0, 0, 0,
           0, 0, 0,    0, 0, 0
9248 DATA  0, 0, 0,    0, 0, 0,     0, 0, 0,     0, 0, 0,
           0, 0, 0,    0, 0, 0
9250 DATA  0, 0, 0,    0, 0, 0,     0, 0, 0,     0, 0, 0,
           0, 0, 0,   45,41,58
9260 DATA 58,38,59,    0, 0, 0,     0, 0, 0,     2,59,60,
           0, 0, 0,    0, 0, 0
9310 READ R: DATA 15
9331 DATA 1,  1,  44,  "GD",  0
9332 DATA 2,  1,  38,  "GD",  0,  3,  1,  38,  "GD",  0
9333 DATA 4,  1,  38,  "GD",  0,  4,  2,  44,  "GD",  0
9334 DATA 5,  1,  38,  "GD",  0,  5,  2,  40,  "GD",  0
```

```
9335 DATA 6,  1,  44,  "GD",  0,  7,  1,  38,  "GD",  0
9336 DATA 7,  2,  44,  "GD",  0,  8,  1,  40,  "GD",  0
9337 DATA 9,  1,  38,  "GD",  0, 10,  1,  40,  "GD",  0
9338 DATA 11, 1,  38,  "GD",  0, 12,  1,  40,  "GD",  0
9500 DATA 1,1,1,1,1, 1,1,1,1,1, 1,1,1,1,1, 1,1,1,1,1,
          1,1,1,1,1, 1,1,1,1,1
9510 DATA 1,1,1,1,1, 1,1,1,1,1, 1,1,1,1,1, 1,1,1,1,1,
          1,1,1,1,1, 1,1,1,1,1
9520 DATA 1,1,1,1,1, 1,1,1,1,1, 1,1,1,1,1, 1,1,1,1,1, 1
9610 MAT READ Z: DATA 3936, 1.0000, .0041708,
                      1968, 1.0000, .0458163
9611             DATA 3936, 1.0000, .0099085,
                      3936, 1.0000, .0083417
9612             DATA 1968, 1.0000, .0014820,
                      3936, 1.0000, .0041708
9613             DATA 3936, 1.0000, .0250042,
                      3936, 1.0000, .08333333
9614             DATA 1968, 1.0000, .0041920,
                      1968, 1.0000, .0041920
9615             DATA  984, 1.0000, .0416666,
                         1, 1.0000, 1.000000
9630 DATA    0,1,10,     0,1,10,      0,1,10,      0,1,10
9631 DATA    0,1,10,     0,1,10,      0,1,10,      0,1,10
9632 DATA    0,1,10,     0,1,10,      0,1,10,      0,1,10
9680 READ   T0,T1,T2    : DATA  0,1,1
```

(2) A set of D and E values of 0.1 and 0.9 for component 6 is entered as C(8) = -1: D = 0.1: E = 0.9. The C value of -1 must appear before the D and E values.

(3) If all components at a branch node are associated with the same C value, it is not necessary to enter a separate C value for each component. If the common C value is 0.349, this value can be entered by C(1) = 0.349: C9 = 1. The program will then assign 0.349 to the C decision for each component at that node.

(4) The default C value is zero (see discussion on topology below for explanation of the reference path for the decision parameter values).

(5) If a G parameter value for component 3 is 4.9, this value is entered as G(3) = 4.9. No C, D, or E values should appear for this component at the node.

(6) If components 4, 6, and 7 form an identifiable subassembly at a node (e.g., a wheelset), they are identified as such by K$(4), K$(6), K$(7) = "*".

The unit path costs are entered into the program in subroutine '02 (program lines 2xxx). Data need be entered only for those paths which have costs. These paths are called cost paths and are a subset of the complete set of paths given by the schematic diagram. Unit path costs for cost path y are entered into the program on program line y = 2030 + 20·(cost path number). Line numbers between 2030 + 20·(cost path number) and 2050 + 20·(cost path number) are available for data of a given cost path. Sufficient space has been provided in the program for 77 cost paths. Additional cost paths can be employed by adding line numbers in a manner similar to that for additional decision parameter values. The additional line numbers are 3590, 3610, etc.; such additional line numbers must then also appear in line 2047. After the cost path data have been entered for any of the cost paths, the statement GOTO 3900 must appear.

The format for entry of the unit path costs is flexible, and allows for a nonlinear cost representation.* The following examples illustrate the format for the cost values:

(1) A unit cost of $50.00 for component 3 (see cost path 4) is entered as C(3) = N(3)*$50.00.

(2) A cost of $25,000 for component 1 (see cost path 30) is entered as C(1) = 25,000.00. Note that this is not a unit cost in that the cost for the path is not dependent on the flow of component 1.

(3) A cost of $17.25 for each <u>defective</u> unit of component 3 (see cost path 40) is entered as C(3) = N(3) * 17.25 * Q(3).

(4) A cost of $5 times the square root of the number of defective units is entered, for component 2, as C(2) = 5.00 * SQR(N(2)*C(2)).

All remaining data are entered in lines which start with the number 9; e.g., 9xxx. These data have comments (REM statements) nearby in the program to describe the data requirements. These requirements are also described in the discussion which follows.

Data in lines 9010 to 9050 describe the size of the model being created. These data are

| Line Number | Quantity | Definition |
|---|---|---|
| 9010 | M2 | Number of components in model. |
| 9020 | Z1 | Total number of nodes (branch, summation, and extra). |
| 9030 | Z2 | Number of branch nodes. |
| 9040 | Z3 | Total number of paths. |
| 9050 | Z4 | Number of cost paths (paths with associated cost). |

*See Example 4.

Examples of the data format can be found in the listing.

The branch nodes -- summation nodes -- extra* nodes are identified in line numbers 9120 - 9129. An example of the data entry is

9120 DATA 1, 2, 3, 4, 0, 5, 6, 0, -1, 7.

In this example, 10 nodes are shown. Of these 10 nodes, 7 are branch nodes (1, 2, 3, 4, 6, 7, and 10). Nodes 5 and 8 are summation nodes (indicated by a zero). Node 9 is an extra node (indicated by -1).

The topology of the schematic diagram is described in lines 9230 through 9269. The data are entered as follows:

9240 DATA 63, 19, 64, 64, 7, 65, 66, 70, 67,

In this example (see Metroliner listing), data for 3 nodes are shown. These are nodes 31, 32, and 33 since the numbers given are the 31st, 32nd, and 33rd sets of 3 numbers. For node 31, the data indicate that the path into the node is path 63. The node is a branch node (see data line 9120 and the discussion above for that data line). For branch nodes, the second number (e.g., 19) gives that departing path from the node defined as the "bad" path. It is this path to which the C, D, E, G, and K$ values for the node are referenced.** The third number (e.g., 64) gives that departing path from the node defined as the "good" path. Node 32 is a summation node (see data line 9120). For summation nodes, the second number (e.g., 7) gives the second path which joins at the node. The third number (e.g., 65) gives the departing path from the node.

Rework data are given in line 9310 and in lines 9331 through 9339. Line 9310 specifies how many reworkings occur in the system described by the schematic diagram. The number given in that line is for the total reworkings

---

*Extra nodes are nodes which have been set aside for possible addition to the schematic diagram.

**As an example, if C(10) = 0 at this node, then none of the units of component 10 arriving on path 63 depart on path 19.

for all components and for all locations. In lines 9331 - 9339 the details of the rework are given. Line 9337 from the Metroliner data is used as an example. That line is

```
9337 DATA 4, 1, 31, "GA", 0,  7, 2, 34, "GD", 0
```

which specifies: Component 4 has its first rework on an outgoing path from node 31. The "good" outgoing path is the one containing the rework and all units are reworked (these are defined by the "GA"). The quality of Component 4 after its rework is 0 (all good). Also, Component 7 has its second rework on the "good" path from node 34. Only the defective units in the path are reworked and the quality for Component 7 after rework is 0.

The next section of data is lines 9500 to 9529. These lines indicate which paths are cost paths and which paths are paths with no (zero) costs. A path with an associated cost (a cost path) is indicated by a 1. A path with no costs is indicated by a 0 (zero). The total number of entries 1 and 0 must be Z3; the total number of entries 1 must be Z4.

State variable data appear next in the program listing, lines 9610 through 9619. The state variables are entered for each component in the order: population size, representative age for the population, and population quality. This is illustrated in the following example line:

```
9612 DATA 122, 1.5517, .0252918,  244., 1.9975, .025803
```

The line specifies that Component 5 has a population size of 122, a representative age of 1.5517 years and a quality of 0.252918*. The line also specifies that Component 6 has a population size of 244, a representative age of 1.9975 and a quality of .025803.

Weibull and population expansion rate data are entered next in the program. The Weibull data are required only for simulations (not for base case or sensitivity analyses). The data are entered successively for each component. The data consist, for each component, of its expansion rate, its

*Data for components 1-4 appear in lines 9610 and 9611.

Weibull slope, and its characteristic life. The data entry is illustrated by the following example line:

```
9630 DATA 0,2,1.82998, 0,2,1.82998, 0,2,1.82998, 0,2,2.32138
```

This line indicates that for Component 1, its expansion rate (in units per year) is zero, its Weibull slope is 2, and its characteristic life is 1.82998 years. The line also indicates that similar data apply to components 2, 3. For Component 4, the expansion rate, Weibull slope and characteristic life are, respectively, 0, 2, and 2.32138.

The final data to be entered into the program are these which control the details of a simulation: those data are entered in line 9680 and provide values for T0, T1, and T2. These quantities are defined as follows:

T0 = The number of years to be simulated. If T0 = 0, then just the base case analysis (year 0 for the simulation) is provided.

T1 = The time step to be used for the simulation: this number is 0.05 to 0.5 years for typical simulations.

T2 = The number of time steps in a simulation at which a printout (of flow results and cost results) is provided. For example, if T2 = 5, then a printout is provided every 5 time steps.

In addition to the data discussed above, the computer program requests (during execution) certain inputs from the user. These are:

| Line Number | Question Asked of User | Response |
|---|---|---|
| 9400 | "DO YOU WANT TOPOLOGY PRINTOUT (1 OR 0)?" | 1 = yes* <br> 0 = no* |
| 9530 | "SENSITIVITY ANALYSIS (1 OR 0)?" | 1 = yes <br> 0 = no |

*A topology printout describes how the paths and nodes are interconnected and where rework is done. Such a printout is useful for debugging of the input data. It allows the user to verify that the schematic diagram is being represented properly for analysis.

(continued from previous page)

| Line Number | Question Asked of User | |
|---|---|---|
| 9535 | "SENSITIVITY ANALYSIS TO START AT (1 TO Z2 FOR BRANCH NODES, -1 TO -Z4 FOR COST PATHS)?" | Enter branch node number (not node number) or cost path number (not path number) |
| 9540 | "HARD COPY (0, 1, OR 2)?" | 0 = None (all output on CRT screen)<br>1 = Population (path 1) quantities only printed on paper<br>2 = all results printed on paper |
| 9550 | "DISC TO BE USED (F OR R)?" | F = Left disc<br>R = Right disc |

For a given minicomputer system, minor modifications to the simulation cost model program may be necessary for the program to execute. These modifications are primarily in line numbers 7020 and 8010 where the device which provides hard copy is identified. In the program listing, this device is 215(132) -- a printer coded 215 which has 132 columns of printing per line.

Program for Calculation of Decision Parameter Values (Table A.3)

The program for the calculation of the decision parameter values is a tool which works with individual branch or summation nodes. The program accepts known values of flow and quality on paths which surround a node. The program then computes values of C (or D and E) for branch nodes and determines unknown flows and qualities for both branch and summation nodes. For branch nodes, the program allows the effects of component interaction to be included as part of the determination of decision parameter values for the individual components. All capabilities described in Section 4.1 are provided by the program.

The program requires no entry of data via program lines -- all data are entered interactively during program execution. Questions asked of the user contain prompting notes which indicate correct responses.

TABLE A.3

PROGRAM FOR CALCULATION OF DECISION PARAMETER VALUES

```
10 REM ************************************************************ REM
20 REM *       SIMULATION COST MODEL DATA CALCULATIONS         * REM
30 REM ************************************************************ REM
34 REM *    "DATACALC"     DISK 16 -- LAST REVISION DATE --- 1/78
36 REM ************************************************************ REM
37 REM
38 REM
40 DEFFN'00"LISTS":SELECT PRINT 005(64):SELECT LIST 005(64)
50 DIM T$1,F$1,Q$1,Q1$2,N(12): INPUT "HARD COPY (Y OR N)",P$
60 GOSUB '02: PRINT HEX(0A0A0A): SELECT PRINT 005
70 PRINT HEX(0A0A0A): INPUT "NODE NUMBER",K7
80 INPUT "BRANCH OR SUMMATION NODE (B OR S)",T$
90 K5=0
100 INPUT "NUMBER OF K$ COMPONENTS",K
110 K5=K5+1: IF K5>K THEN 70
120 IF T$="B" THEN 490: PRINT : PRINT : PRINT "K$ COMPONENT ";K5
;" OF ";K
130 PRINT : INPUT "WHICH FLOW IS UNKNOWN (1=INPUT #1, 2=INPUT #2
, 0=OUTPUT)",F$
140 IF F$<>"1" THEN 180
150 INPUT "2ND INPUT FLOW",F2
160 INPUT "OUTPUT FLOW",F0
170 F1=F0-F2: GOTO 260
180 IF F$<>"2" THEN 220
190 INPUT "1ST INPUT FLOW",F1
200 INPUT "OUTPUT FLOW",F0
210 F2=F0-F1: GOTO 260
220 IF F$<>"0" THEN 130
230 INPUT "1ST INPUT FLOW",F1
240 INPUT "2ND INPUT FLOW",F2
250 F0=F1+F2
260 PRINT :INPUT "WHICH FLOW QUALITY IS UNKNOWN (1=INPUT #1, 2=I
NPUT #2, 0=OUTPUT)",Q$
270 IF Q$<>"1" THEN 320
280 INPUT "2ND INPUT FLOW QUALITY",Q2
290 INPUT "OUTPUT FLOW QUALITY",Q0
300 IF F1<>0 THEN 310: Q1=0: GOTO 410
310 Q1=(Q0*F0-Q2*F2)/F1: GOTO 410
320 IF Q$<>"2" THEN 370
330 INPUT "1ST INPUT FLOW QUALITY",Q1
340 INPUT "OUTPUT FLOW QUALITY",Q0
350 IF F2<>0 THEN 360: Q2=0: GOTO 410
360 Q2=(F0*Q0-F1*Q1)/F2: GOTO 410
370 IF Q$<>"0"THEN 260
```

```
380 INPUT "1ST INPUT FLOW QUALITY",Q1
390 INPUT "2ND INPUT FLOW QUALITY",Q2
400 Q0=(F1*Q1+F2*Q2)/F0
410 GOSUB '02: PRINT : PRINT "SUMMATION NODE - NODE NUMBER ";K7;
"   K$ COMPONENT ";K5;" OF "; K
420 PRINT "OUTPUT FLOW IS ";F0
430 PRINT "1ST INPUT FLOW IS ";F1
440 PRINT "2ND INPUT FLOW IS ";F2:PRINT
450 PRINT "OUTPUT QUALITY IS ";Q0
460 PRINT "1ST INPUT QUALITY IS ";Q1
470 PRINT "2ND INPUT QUALITY IS ";Q2
480 SELECT PRINT 005: GOTO 110: REM * * * * *
490 PRINT : PRINT : PRINT "K$ COMPONENT ";K5;" OF ";K
500 PRINT : INPUT "UNKNOWN FLOW (F=FROM PATH, B=BAD PATH, G=GOOD
 PATH)",F$
510 IF F$<>"F" THEN 550
520 INPUT "BAD PATH FLOW",F1
530 INPUT "GOOD PATH FLOW",F2
540 F0=F1+F2: N=F1/F0: GOTO 630
550 IF F$<>"B" THEN 590
560 INPUT "FROM PATH FLOW",F0
570 INPUT "GOOD PATH FLOW",F2
580 F1=F0-F2: N=F1/F0: GOTO 630
590 IF F$<>"G" THEN 490
600 INPUT "FROM PATH FLOW",F0
610 INPUT "BAD PATH FLOW",F1
620 F2=F0-F1: N=F1/F0
630 N5=N: N=1-(1-N5)↑(1/K)
640 IF K5>1 THEN 750: IF K=1 THEN 760: MAT REDIM N(K): MAT N=CON
: MAT N=(N)*N
650 PRINT "COMBINED SPLIT IS ";N5;", ALL INDIVIDUAL SPLITS WILL
BE ";N
660 PRINT "                                              UNLESS OV
ERRIDDEN"
670 INPUT "OVERRIDE (Y OR N)",Y$: IF Y$="N" THEN 750
680 INPUT "LEAST IMPORTANT COMPONENT",L: T9=1
690      FOR J=1 TO K: IF J=L THEN 720
700 PRINT "INDIVIDUAL SPLIT FOR COMPONENT ";J;" (MUST BE LESS TH
AN COMBINED SPLIT)"
710 INPUT N(J): T9=T9*(1-N(J))
720     NEXT J
730 N(L)=1-(1-N5)/T9: PRINT : PRINT "INDIVIDUAL SPLITS": MAT PRI
NT N
740 INPUT "ARE THESE INDIVIDUAL SPLIT VALUES O.K. (Y OR N)",Y$:
```

```
IF Y$="N" THEN 680
750 N=N(K5)
760 PRINT : INPUT "UNKNOWN DECISION FACTOR OR FACTORS (C=C, DE=D
&E, D=D, E=E)",Q1$
770 IF Q1$<>"C" THEN 790
780 Z=1: C=N: GOTO 1230
790 IF Q1$<>"DE" THEN 970
800 INPUT "UNKNOWN FLOW QUALITY PATH (F=FROM PATH, B=BAD PATH, G
=GOOD PATH)",Q$
810 IF Q$<>"F" THEN 850
820 INPUT "BAD PATH QUALITY",Q1
830 INPUT "GOOD PATH QUALITY",Q2
840 Q0=(F1*Q1+F2*Q2)/F0: GOTO 930
850 IF Q$<>"B" THEN 890
860 INPUT "FROM PATH QUALITY",Q0
870 INPUT "GOOD PATH QUALITY",Q2
880 Q1=1: IF F1=0 THEN 930: Q1=(Q0*F0-Q2*F2)/F1: GOTO 930
890 IF Q$<>"G" THEN 800
900 INPUT "FROM PATH QUALITY",Q0
910 INPUT "BAD PATH QUALITY",Q1
920 Q2=0: IF F2=0 THEN 930: Q2=(Q0*F0-Q1*F1)/F2: GOTO 930
930 Z=1: IF Q0=0 THEN 940: Z=Q1/Q0
940 GOSUB '01
950 D=N*Z: E=0: IF Q0=1 THEN 1230
960 E=N*(1-Z*Q0)/(1-Q0): GOTO 1230
970 IF Q1$<>"D" THEN 1100
980 E=0: Q1=1
990 INPUT "UNKNOWN FLOW QUALITY PATH (F=FROM PATH, G=GOOD PATH)"
,Q$
1000 IF Q$<>"F" THEN 1030
1010 INPUT "GOOD PATH QUALITY",Q2
1020 Q0=(F1*Q1+F2*Q2)/F0: GOTO 1070
1030 IF Q$<>"G" THEN 990
1040 INPUT "FROM PATH QUALITY",Q0
1050 Q2=0: IF F2=0 THEN 1070
1060 Q2=(Q0*F0-Q1*F1)/F2
1070 Z=1: IF Q0=0 THEN 1080: Z=Q1/Q0
1080 GOSUB '01
1090 D=N*Z: GOTO 1230
1100 IF Q1$<>"E" THEN 630
1110 D=1: Q2=0
1120 INPUT "UNKNOWN FLOW QUALITY PATH (F=FROM PATH, B=BAD PATH)"
,Q$
1130 IF Q$<>"F" THEN 1160
```

```
1140 INPUT "BAD PATH QUALITY",Q1
1150 Q0=(F1*Q1+F2*Q2)/F0: GOTO 1200
1160 IF Q$<>"B" THEN 1120
1170 INPUT "FROM PATH QUALITY",Q0
1180 Q1=1: IF F1=0 THEN 1200
1190 Q1=(F0*Q0-F2*Q2)/F1
1200 Z=1: IF Q0=0 THEN 1210: Z=Q1/Q0
1210 GOSUB '01
1220 E=0: IF Q0=1 THEN 1230: E=N*(1-Z*Q0)/(1-Q0)
1230 REM * * * * * BRANCH POINT PRINTING
1240 GOSUB '02: PRINT : PRINT "BRANCH NODE - NODE NUMBER ";K7;"
  K$ COMPONENT ";K5;" OF "; K
1250 PRINTUSING 1260,F0: PRINTUSING 1270,F1,N5: PRINTUSING 1280,
F2,N
1260% INPUT FLOW (COMBINED) = #########
1270% BAD PATH FLOW (COMBINED) = #########              N1 (COMBI
NED) = #.#######
1280% GOOD PATH FLOW (COMBINED) = #########           N1 (INDIVID
UAL) = #.#######
1290 PRINT : IF Q1$<>"C" THEN 1300: PRINT "Q1 = ";Z,"C = ";C: SE
LECT PRINT 005: GOTO 110
1300 PRINTUSING 1310,Q0: PRINTUSING 1320,Q1,Z5: PRINTUSING 1330,
Q2,Z
1310% INPUT FLOW QUALITY (COMBINED) = #.#######
1320% BAD PATH FLOW QUALITY (COMBINED) = #.#######     Q1 (COMBI
NED) = ##.######
1330% GOOD PATH FLOW QUALITY (COMBINED) = #.#######  Q1 (INDIVID
UAL) = ##.######
1340 PRINT "D (INDIVIDUAL) = ";D,"E (INDIVIDUAL) = ";E
1350 SELECT PRINT 005: GOTO 110: REM * * * * *
1360 DEFFN'01
1370 Z5=Z
1380 IF N5<>1 THEN 1390: Z=1: RETURN
1390 Z=(Z5*N5*(1-N)+N-N5)/(N*(1-N5))
1400 RETURN
1410 DEFFN'02
1420 IF P$="N" THEN 1430: SELECT PRINT 215(132)
1430 RETURN
```

The program first asks for the number of the node under consideration. This number is that on the schematic diagram and is included in the output for proper referencing of results. The program then asks if the node is a branch or summation node. The program also asks how many components at the node are part of an identifiable subassembly.* If the node is a summation node (the simpler case), the program asks for flows and qualities. Flows on two of the three paths and qualities on two of the three paths are requested. The program then computes the remaining flow and quality. If the node is a branch node, the program proceeds as follows.

For a branch node, the program first requests flow data for the component on two of the three paths. If a component is being considered which is not part of, or not the first component of, an identifiable subassembly, the actions in the next paragraph are skipped. If the component is the first of an identifiable subassembly, the program proceeds as follows.

For a component k which is the first of an identifiable subassembly, the program computes a proportion $C^*$ as described in Section 4.1.1. The user can override this proportion and must then specify the individual proportions for all but one of the components in the subassembly. In this, the procedure and equations given in that section are followed.

Next, the program requests that the user enter the type of decision which occurs at the node for the component. If the decision is a C decision, the C parameter value for the component and the remaining unknown flow is computed.

If the decision is a D and E decision, quality data are requested of the user. These quality values can be those for any two of the three nodal paths. If the decision is a D decision (E = 0) or an E decision (D = 1), the quality data are also requested of the user. In these cases, the

---

*If a component is being considered which is not part of an identifiable subassembly, the response of the user is 1.

user need supply a quality value on only one path. The program then computes the D and/or E value and the remaining unknown path flow and path quality.

At this point, the program is finished with the component. If the component just considered is part of an identifiable subassembly, the program then proceeds to the next component in that assembly. If the component is the last component in the subassembly, or if the component is not part of an identifiable subassembly, the program starts its execution over (the program again asks for the node number, etc.). Another component at the same node can be treated or another node can be considered. By working successively through the various components and nodes, the user can "hand calculate" the base case analysis. In so doing, the user will identify gaps in the raw data and will obtain values for all the decision parameters in the simulation cost model.

## APPENDIX B

## AMCOACH FLEET: MAINTENANCE AND DATA FROM THE COMPUTERIZED MAINTENANCE ANALYSIS PROGRAM

This appendix provides a brief description of the procedures and data storage process used in maintaining the Amcoaches. The majority of information provided in this description was obtained by visiting the 30th Street (Philadelphia) Amtrak Maintenance facility. That facility maintains about 275 of the approximately 492 Amcoaches in service.

The maintenance procedure contains two parts: the scheduled or program maintenance and the unscheduled or bad ordered maintenance. Each of these is described separately below.

The program maintenance is generally performed by the facility to which a car is assigned. If that facility is overloaded, cars may be assigned for program maintenance to another facility. The maintenance can be either a monthly, a 90 day, a 180 day, a 270 day, or a 360 day (days are measured from the previous yearly maintenance). The 360 day is the most comprehensive, followed by the 180, the 90 - 270, and the monthly. The 90 and 270 day maintenance are essentially the same. The monthly inspections are just spot checks and are not formally considered part of the program. The items checked under each of the three program maintenance categories are listed in forms completed during the maintenance operation.

When a car enters the Philadelphia facility, it first goes to a pit area. At the pit, the trucks are inspected and serviced. Servicing involves, if necessary, replacement of brake components, suspension components, or wheel-axle assemblies. Secondary suspension springs and air bags are replaced by jacking up the car body — the truck is not removed from the car. If wheel-axle assemblies are defective, the entire assembly is removed and replaced with another wheelset. The wheelset includes the wheels, bearings, axle, and disc brake plates.

After the pit area, the car goes to track 32 for other servicing. This servicing includes car cleaning, car repair, etc. Wheel turning, if necessary, is done under the car. A separate enclosed track area houses the in-place wheel turning machine.

At Philadelphia on a given day, about 15 cars are in the shop for the program. Between 0 and 15 or so may be in the shop for unscheduled maintenance.

The unscheduled maintenance can arise because of a terminal inspection bad order, a conductor bad order, or a monthly inspection bad order. No attempt is made to send the bad ordered car back to the maintenance facility which ordinarily performs its program service — the most convenient facility is used. The problem with the car is attended to and then the car is placed back into service. The date of the next program service is not affected by the performance of unscheduled maintenance on the car.

According to the conversations with the foremen, Amtrak performed all the service since Amtrak took over the Philadelphia facility. The majority of the Amcoaches were put into service since that time. During the initial stages of Amcoach use (late 75 and early 76), Budd personnel assisted Amtrak in the maintenance.

Several forms are associated with the maintenance of the Amcoaches. These are as follows:

1. The Maintenance Analysis Program Card (Map #21A) records that the program maintenance was done to the car. This card stays in the car.

2. The Car Condition Report (Form 1000A) is used by the conductor or other Amtrak employee to record problems perceived during car operation. This card stays in the car and is referred to during program servicings and during unscheduled servicings. When the card gets full or becomes soiled, it is removed at a program service and is filed with the program service records. The place that the card is filed depends on where the program service is done at the time the card is replaced.

3. The shop sheet contains a record of all maintenance actions conducted by the Philadelphia shop during a given day. The sheet contains space for 12 cars. The sheet will list whether the car is in the shop for a program service (and, if so, which one) or for a specific problem (and, if so, what that problem is). If the car is in the shop for a specific problem, the shop sheet will show the problem as diagnosed by the Philadelphia inspector (not the problem as suspected by the conductor or other Amtrak employee on the 1000A Form).

4. The Maintenance Analysis Program Work Sheet (old Form) and the Maintenance Analysis Program Original Record of Repairs (new Form) list work performed on the car. The old Form listed all work performed during program servicings. For unscheduled servicing, this sheet was not filled out. The Form was filed in the car file at the maintenance location where that particular program service was performed. The new Form is filled out for both program and unscheduled servicings. The information from the new Form is entered into a computer system for on-line storage in Washington, D.C. All maintenance performed on each car is to be available when the system is fully operational (see MAP description below).

5. Inspection Forms — These Forms describe the inspections which must be performed at the 90, 180, 270, or 360 day maintenances. The Forms are filed in the car file at the maintenance facility which did the service. The Forms include:

   a. The Monthly Inspection Report
   b. The 3 Months Inspection Report
   c. The 6 Months Inspection Report
   d. The 3 Months E Cleaning Report
   e. The Periodic Journal Bearing Lubrication Procedure
   f. The Wheel and Coupler Inspection Report
   g. The Inbound Inspection Report and Dispatchment Report — Layover.

In order to establish the events which occurred in the life of a particular car, access to records containing several of the above forms is necessary. For events which occurred since July 1977, the computer record produced from the new Work Sheet (4) is sufficient. This computer record centralizes all maintenance records for each car regardless of where the maintenance was performed (see MAP description below). For events which occurred prior to July 1977, a rather difficult search procedure is necessary. This procedure includes:

1. Review of the file for the car in Philadelphia. This file contains the details of all program maintenance on the car <u>for those program maintenances performed in Philadelphia</u>.

2. Review of the shop sheets for Philadelphia. These shop sheets will show the unscheduled maintenance performed on the car <u>in Philadelphia</u>.

3. Review of the records of the other maintenance locations. At each location, the car file will contain the records (i.e., Work Sheet Inspection Forms, and (possibly) 1000A sheets) for the program

maintenances performed on that car by that facility. The shop sheet will contain the record of the unscheduled maintenance performed on that car at that facility.

The computerized Amcoach Maintenance Analysis Program (MAP) centralizes all maintenance records for each car regardless of where the maintenance was performed. This computerized system started operation in mid 1977. It has gradually become fully operational since that time.

The Maintenance Analysis Program is useful for the simulation cost model in that it can provide data on the occurrence rate of various maintenance labor operations and on the associated costs. The occurrence rate allows various flows in the schematic diagram to be established so that values of the decision parameters can be computed. The costs allow unit costs to be established on some of the paths in the diagram.

A typical output which the Maintenance Analysis Program produces and which contains flow and cost data is shown as Table B.1. In this table various repair operations are listed for the Philadelphia facility. For each operation, the description, the repair, the number of repetitions, and labor costs are shown. It should be noted that the labor costs are not actual costs but are costs computed on a standard rate of approximately $7 per hour.

In Table B.1, several rows are shaded. These rows represent repair operations associated with the truck. Typically, most of the repair operations do not involve the truck.

The MAP data will soon become the best source of Amcoach data. However, a period of time should be allowed to pass before MAP data are used extensively for the simulation cost model or for other economically oriented purposes.

## TABLE B.1

## NATIONAL RAILROAD PASSENGER CORPORATION

REPORT NO : 15-20 MAINTENANCE FACILITY MANAGEMENT SYSTEM PAGE NO. 2

RUN DATE: 10/01/77 FACILITY DIRECT LABOR COST BY REPAIR REPORT

7/1/77 to 10/1/77

FACILITY: PHILADELPHIA PENN CO

| REP CODE | REPAIR DESCRIPTION | MONTH-TO-DATE NO. REPS | ACTUAL LABOR COSTS | STANDARD LABOR COSTS | TOTAL LABOR COSTS | YEAR-TO-DATE NO. REPS | ACTUAL LABOR COSTS | STANDARD LABOR COSTS | TOTAL LABOR COSTS |
|---|---|---|---|---|---|---|---|---|---|
| 0406 | END DOOR WIRING | 7 | $57 | $0 | $57 | 8 | $62 | $0 | $62 |
| 0468 | MAP 1804,6MO.INSPECTION-AMFL'T | 12 | $57 | $0 | $57 | 12 | $57 | $0 | $57 |
| 0416 | SIDE DOOR WIRING | 8 | $49 | $0 | $49 | 10 | $62 | $0 | $62 |
| 7395 | DECELLOSTAT | 4 | $49 | $0 | $49 | 5 | $54 | $0 | $54 |
| 0275 | SLACK ADJUSTER, PASSENGER TYPE | 1 | $14 | $0 | $14 | 1 | $14 | $0 | $14 |
| 0671 | PUBLIC ADDRESS SYSTEM | 8 | $38 | $0 | $38 | 24 | $176 | $0 | $176 |
| 0472 | MAP 3604,1YR.INSPECTION-AMFL'T | 8 | $38 | $0 | $38 | 8 | $38 | $0 | $38 |
| 0414 | SIDE DOOR OPERATOR MOTOR | 6 | $37 | $0 | $37 | 6 | $37 | $0 | $37 |
| 0784 | DIAPHRAGM | 0 | $0 | $0 | $0 | 1 | $17 | $0 | $17 |
| 0600 | INTERIOR-GENERAL | 5 | $34 | $0 | $34 | 5 | $34 | $0 | $34 |
| 0544 | KITCHEN-REFRIGERATOR | 2 | $33 | $0 | $33 | 3 | $43 | $0 | $43 |
| 0402 | END DOOR PUSH PLATES | 6 | $32 | $0 | $32 | 13 | $67 | $0 | $67 |
| 0720 | EXTERIOR LIGHTS. | 4 | $31 | $0 | $31 | 4 | $31 | $0 | $31 |
| 0299 | BRAKE INDICATOR LIGHT | 3 | $29 | $0 | $29 | 9 | $64 | $0 | $64 |
| 0415 | SIDE DOOR CONTROL PANEL | 2 | $28 | $0 | $28 | 2 | $28 | $0 | $28 |
| 0704 | CONDENSOR | 0 | $0 | $0 | $0 | 1 | $14 | $0 | $14 |
| 0389 | BATTERY CHARGER | 7 | $27 | $0 | $27 | 10 | $66 | $0 | $66 |
| 0387 | TRAINLINE RECEPTICLE | 2 | $26 | $0 | $26 | 2 | $26 | $0 | $26 |
| 0762 | WINDOWS-OUTER | 4 | $26 | $0 | $26 | 41 | $254 | $0 | $254 |
| 0605 | INTERIOR EXIT LIGHTS | 5 | $24 | $0 | $24 | 8 | $45 | $0 | $45 |
| 0798 | VESTIBULE CURTAIN | 5 | $23 | $0 | $23 | 13 | $58 | $0 | $58 |
| 0403 | END DOOR ELECTRO/PNEU OPERATOR | 3 | $22 | $0 | $22 | 11 | $50 | $0 | $50 |
| 0507 | FIRST AID KIT | 6 | $22 | $0 | $22 | 10 | $33 | $0 | $33 |
| 0201 | SUSPENSION AIR SPRINGS | 5 | $20 | $0 | $20 | 6 | $28 | $0 | $28 |
| 0176 | SHOCK ABSORBER-AIRPLANE TYPE | 3 | $19 | $0 | $19 | 5 | $27 | $0 | $27 |
| 0623 | HOT WATER HEATER | 3 | $18 | $0 | $18 | 14 | $208 | $0 | $208 |
| 0548 | KITCHEN-COFFEE MAKER | 3 | $18 | $0 | $18 | 5 | $52 | $0 | $52 |
| 0405 | END DOOR CONTROL PANEL | 2 | $17 | $0 | $17 | 4 | $28 | $0 | $28 |
| 0731 | EXPANSION VALVES | 2 | $16 | $0 | $16 | 3 | $26 | $0 | $26 |
| 0305 | BATTERY CABLES | 2 | $15 | $0 | $15 | 4 | $47 | $0 | $47 |
| 0292 | BUDD RUBBER SHOE PAD | 1 | $14 | $0 | $14 | 4 | $57 | $0 | $57 |
| 0551 | KITCHEN-HOT PLATE | 3 | $14 | $0 | $14 | 4 | $17 | $0 | $17 |
| 0703 | FREON PIPING | 2 | $14 | $0 | $14 | 4 | $43 | $0 | $43 |
| 2136 | UNCOUPLING LEVER | 1 | $14 | $0 | $14 | 3 | $28 | $0 | $28 |
| 0521 | LOUNGE BAR ICE STORAGE | 1 | $12 | $0 | $12 | 1 | $12 | $0 | $12 |
| 0531 | BUFFET-MICROWAVE OVEN | 2 | $12 | $0 | $12 | 3 | $26 | $0 | $26 |
| 0547 | KITCHEN-OVEN | 2 | $12 | $0 | $12 | 3 | $34 | $0 | $34 |
| 7625 | TRAINLINE RECEPTACLE-27 POINT | 1 | $12 | $0 | $12 | 2 | $23 | $0 | $23 |

This period of time, lasting perhaps 2 - 3 years, will allow all Amtrak personnel to become thoroughly familiar with the system. In addition, during that time the number of repair operations should become sufficiently large that statistically valid information can be obtained.

## APPENDIX C

## TURBOTRAIN TRUCK

The turbotrain truck was intended, during the early months of the contract, to be one of the subjects for the simulation cost model. To obtain information and data on that truck, a visit was made to the Canadian National Railroad (CNR) on April 26 and 27, 1977. The CNR has operated a turbotrain for many years and consequently represents a source of data for the truck.

During later months of the contract, it was decided not to apply the simulation cost model to the turbotrain truck. However, since information and data were obtained from the visit, they have been organized and are presented in this Appendix.

### GENERAL

The CNR turbotrain is a unit train consisting of two power dome (P.D.) cars (one at each end of the train) and seven intermediate cars (I.C.). Each P.D. car has one dual axle (D.A.) truck with each axle powered through an axle mounted gear box. These gear boxes are driven from a cab mounted "collector" gear box which in turn is powered by two P&WA PT-6 gas turbines.

A single axle (S.A.) truck is employed between each car - P.D.'s and I.C.'s. Thus, there are eight S.A. trucks per train. All cars are mechanically attached such that the entire train becomes an integrated unit. Once the train is assembled, cars are not added, subtracted, or replaced - except for changes in "mission" - as approximately three days is required to "break" a car from the train.

Three trains are employed on the twice per day Montreal-Toronto run (667 miles round trip). Thus, each train is in revenue service 67% of the time (one train is always either undergoing major maintenance or is in reserve). Each train averages approximately 140,000 miles per year (accounting for once-per-day trips on Sundays).

TRUCK DEFINITIONS

D.A. Primary Truck is removed from the P.D. car as a unit and consists of wheels, axles, gear boxes, journal bearings, primary springs, side frames, brake shoes, brake actuators, brake linkages, and center pin bushing/housing.

D.A. Secondary Truck is attached to the P.D. car and consists of the bolster, center pin, torsion springs, dampers, secondary springs (air bags), side bearings, and lateral stops.

S.A. Primary Truck is removed from between cars as a unit and consists of wheels, axle, journal bearings, primary springs, torsion springs, lateral stops, transom beams, brake shoes, actuators, and linkage, bell crank, and lower guidance arms.

S.A. Secondary Truck is attached to each car and consists of the upper guidance arms, walking beams, secondary springs (air bags) and upper suspension arms.

COMPONENT SPECIFICS

(1) Primary Springs are "Lord mounts" on both single axle (S.A.) and double axle (D.A.) trucks similar to the Budd "Pioneer 3". They are replaced on the average about every 200,000 miles.

(2) Secondary springs are air bags and are very seldom replaced on D.A. trucks. Approximately 12 S.A. air bags are replaced every year indicating an average life of about 560,000 miles. S.A. suspension rod end bearings are rebuilt on the average every 250,000 miles. The most aggravating problem with the D.A. secondary suspension is maintenance of the bearings which attach the air bag supporting plate to the P.D. car - because bolster removal is required.

(3) Dampers are of two types - viscous on the D.A. secondary truck and rubber shear (torsion springs) on the D.A. secondary truck and S.A. primary truck. The viscous dampers are of questionable value (not used on Amtrak turbotrain) and are replaced only if the bolster has to be removed for other reasons. Torsion springs last about 200,000 miles.

(4) Bearings are standard Timken XP's. Bearings have presented no problems (only a total of two failures since 1968). They go through standard rework procedure at the time of each wheel change (approximately 42,000 miles). They are not relubed between rework. Bearings are inboard on D.A. trucks and outboard on S.A. trucks.

(5) Frames per se are not a problem. Transom beams on S.A. trucks are starting to give problems around dowel pin and cap screw holes and are being modified as major truck refurbishment becomes necessary. D.A. truck side frame bushings are replaced at about 500,000 miles. No center pin bearings have ever been replaced.

(6) Axles/gear boxes are probably the biggest grief. Gear boxes require major maintenance about every 80,000 miles and this requires complete disassembly of the truck including wheel removal. Primary problems are high speed pinion and jack shaft bearings. Gears themselves last about 250,000 miles. All gear box work is done by P&WA which requires that gear box be sent to their facility in Longueuil, Quebec (after wheel removal at the wheel shop). In addition, some gear box work is done about 30% of the time that wheelsets are pulled for attention (approximately 14,000 miles). This usually consists of torque arm work, jack shaft bearings, or labyrinth seals. In the latter case, wheels must be pulled. Indications of gear box problems are leakage, low oil pressure, and audible noise. Axles themselves must be replaced after about three wheel changes because of fit problems.

(7) Wheels are turned on the average of 14,000 miles and are good for two turnings (42,000 miles total life). Primary problem is high heat dissipation from tread brakes (train does not employ dynamic braking) resulting from the combination of high speed operation and few number of wheelsets. To avoid undue heat cracking problems, soft wheels are used which leads to low wear life. Wheels on D.A. trucks are turned under the truck using a standard wheel turning machine. However, the truck is removed from the car and sent to the wheel machine for this operation. S.A. truck wheelsets are removed from the truck for turning, but the truck is not removed from the car (primary springs stay with the wheelset).

(8) Brake shoes are replaced daily (at Montreal), thus have a useful life of 667 miles. Shoe replacement is straightforward (in the absence of snow) and requires no other component removal. Brake rigging (pins and bushings) require replacement every 9 to 12 months (100,000 to 140,000 miles).

(9) Pneumatic systems are employed for brakes and car leveling (secondary springs). No particular pneumatic system problems were noted (although we did not ask specifically about leveling valves which we know are a problem on the Metroliner).

(10) Alternators per se are not employed. Speed measurement is accomplished by a standard magnetic pick-up looking at a notched disc fastened to the end of the axle. No problems were noted.

(11) Bolsters are employed on the D.A. truck. The side bearings as well as other previously mentioned secondary suspension components are attached to the bolster. Side bearings are easily replaceable (after truck removal) Teflon pads and are replaced at about six month intervals (approximately 70,000 miles). This is normally done only at truck removal (wheel work) time.

(12) Motors (traction) are not employed on the turbotrain.

OPERATION TIMES

| | | |
|---|---|---|
| Remove S.A. truck | = | 3 men, 4 hours |
| Install S.A. truck | = | 3 men, 4 hours (assumed) |
| Remove D.A. truck | = | 2 men, 6 hours |
| Install D.A. truck | = | 2 men, 6 hours (assumed) |
| Remove and replace gear box | = | 2 men, 6 hours (complete D.A. truck disassembly) |

SUMMARY OF PERIODIC (PROGRESSIVE) INSPECTIONS

| Inspection Number | Required Equipment | Frequency (Days) | Description |
|---|---|---|---|
| 108 | None | 1 | Dual Truck Area Inspection<br>Visual wheels inspect (dual axle) trucks for cracks broken welds slider plate metal-metal contract. Bolts and studs. Teflon extrusion pilot plate and top of rail 3"-6" clearance<br>oil leaks<br>universal joints<br>lateral rubber bumper<br>center pin<br>leaking/over heat/broken roller bearings |
| 110 | None | 1 | Single Axle Truck Inspection<br>Same as Inspection Number 108. Air suspension (visual rubber) |
| 115 | Dip Stick and Oil | 1 | Axle Gear Box Lubrication Oil Level Check<br>Axle gear box lubrication |

| Inspection Number | Required Equipment | Frequency (Days) | Description |
|---|---|---|---|
| 118 | Grease/Gun Jacks | 30 | Walking Beam Lubrication<br>Grease ball joints |
| 119 | None | 30 | Dual Axle Truck & Drag Link Bolt Inspection<br>Dual axle truck bolt security check |
| 120 | None | 30 | Single Axle Truck & Guidance Arm Bolt Inspection<br>Same as Inspection Number 119 |
| 121 | 6" Rule | 30 | Single Axle Truck & Guidance Arm Bolt Inspection<br>Check air suspension on dual axle. Truck clearance and level check. |
| 128 | 6" Rule | 30 | Single Axle Air Suspension System Check<br>Check air suspension on single axle. Truck clearance and level check. |
| 130 | Wheel Gage | 30 | Wheel Inspection<br>Visual wheels measure flange thick, height, range thickness wheel diameter. |
| 132 | Wrench<br>Solvent<br>Comp. Air | 30 | Axle Gearbox Oil Screen Filter Inspection<br>Axle filter inspection. Remove screen-clean. Replace on each dual axle trucks DC. |
| 133 | Grease Gun & Grease | 30 | Propeller Shaft Slip Coupler Lubrication<br>Shaft coupler |
| 134 | O rings, fluid<br>Torque Wrench | 360 | Main Lube System, Collector Gearbox and Axle Gearbox Oil Replacement<br>Change oil in gearbox filter to O.C. for ultrasonic cleaning. |

| Inspection Number | Required Equipment | Frequency (Days) | Description |
|---|---|---|---|
| 136 | Mirror/Scale Flashlight | 90 | Single Axle Truck Clearance Check<br>Clearance check 5/16 ± 1/16 Clear - bearing flange to truck assembly |
| 141 | Grease Gun etc. | 90 | Drag Link Lubrication<br>Lubrication drag link |
| 144 | None | 1080 | To Inspect Centre Pin Rubber Bushing<br>Look, see, report, put back rug |
| 147 | Grease Gun | 360 | Wheel Bearing Lubrication<br>Lubrication Timken wheel bearings 12 oz. annually |
| 149 | Metal Spacer Up Stop | 90 | Dual Axle Truck Side Bearing Inspection<br>Side bearing inspection (dual axle truck)<br>Put in lock blocks.<br>Lift car.<br>Look for wear.<br>If bad check ball of spherical bearing on bolster. |
| 150 | Lock-wire Tool and Torque Wrench | 150 | Dual Axle Truck Area Torque & Lockwire Check<br>Check torques/many nuts (dual truck) |
| 151 | Lock-wire Tool & Torque Wrench | 150 | Single Axle Truck Area Torque & Lockwire Check<br>Single axle truck |
| 153 | Grease | 90 | Lub. of the Single Axle Guid. System, Bellcrank Bearings<br>Lubrication guidance and bell-crank bearing |

| Inspection Number | Required Equipment | Frequency (Days) | Description |
|---|---|---|---|
| 157 | Flashlight | 1 | Inspection of Levelling Valve Inspection<br>Levelling Valve.<br>Visual wear/secure/missing bolts enlongated bolt holes. |
| 302 | None | 1 | Dual Axle Brake Shoe Slack Adjuster Adjustment<br>Brake shoe slack adjustment. Check/adjust clearance between shoes and wheel. Fix at 5/8". |
| 303 | None | 1 | Tread Brake Components Inspection Rotochamber Air Leakage Check<br>Inspection for wear. Condemn at 3/8" thick. New = 1-3/4". Check broke/cracked pins and bushing wear 1/16 maximum clear.<br>Must have 3/4" to leave station inspection rotochamber boot |
| 304 | None | 1 | Rotochamber Air Leakage Check<br>Check rotochamber for leaks. Listen for leak. |

# APPENDIX D

## SPECIFICATION ON HIGH SPEED PASSENGER TRAIN TRUCKS

This appendix presents two tables which address the topic of specifications on high speed passenger train trucks. The first table, Table D.1, gives a list of those areas where specifications could be applied. The second table, Table D.2, outlines a number of specific features of railway truck specifications which are desirable and may have been omitted, overlooked, or neglected. For the most part, Table D.2 addresses the performance characteristics of a truck. Data on these characteristics are needed to determine the level and frequency of the maintenance required to keep a truck within its allowable range of performance. Maintenance criteria must be considered at the initial stage of design. These criteria can be specified, incorporated and modified appropriately as the final design is developed and approved.

TABLE D.1

AREAS FOR HIGH SPEED PASSENGER TRUCK SPECIFICATIONS

Design Speed

Acceleration

Deceleration

Design Load

- Maximum Static Axle Load
- Short Duartion Static Overload
- Dynamic Load
- Component Dynamic Loads

Maximum Weight

Design Life

Design Braking

- Dynamic
- Friction
- Emergency

Wheel Out of Round

Wheel Balance

Equalization

Curving Performance (Depends on Track and Carbody)

Ride Quality Requirements (In Conjunction with Car)

Primary Suspension Rate

Secondary Suspension Rate

Vibration Frequencies

Noise (In Conjunction with Car)

Clearance Envelope (In Conjunction with Car)

Safety Springs

Maintainability

Reliability

Guaranteed Components

Quality Control in Manufacturing

## TABLE D.2

## FEATURES DESIRABLE IN TRUCK SPECIFICATIONS

1) The specification should include a definition of the ride quality objectives as well as a detailed definition of the track input. This will enable the manufacturer to design a truck and suspension system to a clear-cut design requirement.

2) The car body elastic properties must be given to perform meaningful ride quality analysis. The characteristics of the car body above the secondary suspension must be known to the truck manufacturer.

3) Modeling simulations should be required of the manufacturer to enable the characteristics of the system to be more completely understood, and to allow revisions to be made in the design stage.

4) Provisions should be made for life testing of truck components by simulating the expected load environment. This will allow the manufacturer to detect any flaws in the components or their associated attachments.

5) Full scale structural fatigue tests should be performed on a prototype truck structure.

6) Full scale dynamic truck tests should be performed in the laboratory to study the behavior of the suspension system with all its components to verify at an early stage that all components are compatible and that desired system performance is achieved.

7) An evaluation of a completely instrumented prototype vehicle should be provided. The purpose of this would be to verify performance before committing to final production.

8) Truck specifications should include data on the property's existing maintenance facilities and practices and should require the manufacturer to provide an estimate of the maintenance cost for the assumed life of the truck using the specified maintenance facilities. The builder should also specify a maintenance plan for the truck.

# APPENDIX E

## REPORT ON INVENTIONS

The work described in this report concerns the application of a methodology, the simulation cost model (SCM), to the economic aspects of maintaining high speed passenger train trucks. Because the work was not concerned with devices, no inventions were developed. However, the work did result in a methodology which can be applied to economic systems beyond those associated with passenger train truck maintenance. The systems most appropriately treated by the SCM consist of large fleets of individual units. Each unit contains several components and each component is interrelated with the other components in its unit through cost or system actions. For such a system, the SCM technique provides a consistent means for its characterization, a process for determining the data requirements, a developed computer program, and a set of specific useful outputs. These outputs include a quantitative description of current (present time) annual system operation and annual costs, a sensitivity analysis which indicates quantitatively the most costly portions of the system, and projections of future system operation and costs.

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