NO. UMTA-MA-06-0029-74-1

AVAILABILITY ANALYSIS OF DUAL MODE SYSTEMS

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APRIL 1974

FINAL REPORT

Prepared for

DEPARTMENT OF TRANSPORTATION

URBAN MASS TRANSPORTATION ADMINISTRATION

Office of Research and Development

Washington DC 20590

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
UMTA-MA-06-0029-74-1		

4. Title and Subtitle	5. Report Date
AVAILABILITY ANALYSIS OF DUAL MODE SYSTEMS,	April 1974
	6. Performing Organization Code
7. Author(s)	8. Performing Organization Report No.
Charles R. Toye	DOT-TSC-UMTA-74-4
9. Performing Organization Name and Address	10. Work Unit No. (TRAIS)
Department of Transportation, Transportation Systems Center, Kendall Square, Cambridge MA 02142	MA-06-0029
	11. Contract or Grant No.
	13. Type of Report and Period Covered
12. Sponsoring Agency Name and Address	Final Report Sep. 1973 - Mar. 1974
Department of Transportation, Urban Mass Transportation Administration, Office of Research and Development, Washington DC 20590	14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

The availability calculation of a complex ground automated transportation system such as that described in the Phase III scenario of the Urban Mass Transportation Administration (UMTA) dual mode transit program is most understandable when expressed in terms of the fraction of system time lost due to either passenger or vehicle delays. This involves both system reliability and maintainability, including the number of system failures per time interval, their effects, and corrective action times required to avoid vehicle delays.

The analytical procedures presented herein define a method of evaluating the effects of failures in a complex dual mode system based on a "worst" case steady state analysis. The computed result is an availability figure of merit and not an absolute prediction with associated confidence levels of system availability. The advantage of this procedure is that it avoids the use of a dynamic network traffic flow simulation which is both costly and time-consuming.

17. Key Words	18. Distribution Statement
Availability, Monte Carlo Procedure, Reliability, Simulation	DOCUMENT IS AVAILABLE TO THE PUBLIC THROUGH THE NATIONAL TECHNICAL INFORMATION SERVICE, SPRINGFIELD, VIRGINIA 22151.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	23	

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

PREFACE

In a dual mode transportation system, vehicles are capable of operating on conventional streets in a manual mode, and also, on specially constructed guideways in a completely automated mode.

During September 1973, UMTA awarded three contracts for the design phase of a Dual Mode Transit System (DMTS) development program. The awards were made to the Rohr Corporation, Chula Vista, California; General Motors Corporation, Warren, Michigan; and to Transportation Technology, Incorporated, Denver, Colorado.

The three companies will be engaged in the first phase of UMTA's dual mode program designed to apply new technologies to the improvement of existing means of mass transportation. The program is directed towards reducing traffic congestion and improving personal mobility within medium-to-large urban areas.

The objective of this dual mode program is to combine the best automated transit such as the Personal Rapid Transit (PRT) system currently being demonstrated in Morgantown, West Virginia with the best aspects of modern bus technology. The dual mode concept combines two methods of operation: a driver-operated mode on surface streets or highways and an automated mode on fixed guideways.

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1. INTRODUCTION

This report discusses the availability procedures that were given to the contractors who were selected to participate in Phase I of the UMTA Dual Mode Program. The procedures were to be used as guidelines for the contractors in determining a relative availability figure of merit for their proposed system designs. An availability estimate is usually derived during the long concept development or design phase of a system. In a ground transprotation system, such as dual mode, it involves the calculation of either passenger or vehicle delays based on the system's reliability and maintainability, including the number of system failures per time interval, their effects, and corrective action times required to avoid delays. In Phase I of the Dual Mode Program, the emphasis was placed on vehicle delays derived from a "worst" case steady state analysis. This avoided the use of a dynamic network traffic flow simulation which is required for the computation of passenger delays and deferred until Phase II of the program.

The approach taken encompasses fault tree and failure mode and effect analyses. The novel aspect of this approach is the use of the Monte Carlo technique to determine the physical location of failed vehicles in the system (on or off the guideway, in station berths, or at various merge/demerge sectors).

The requirements of the Phase III scenario are discussed with respect to types of stations, guideway sectors, passenger flow and network configurations. The procedures consist of:

a. Dividing the system into similar kinds of major hardware and software subsystems and components as determined from its functional characteristics,

b. Determining the number of vehicles per section based on speed, percentage of vehicle/guideway occupancy, and a steady state passenger seated flow rate,

c. Conducting an appropriate failure mode and effect analyses (FMEA) based on the system design, reliability, maintainability, and safety practices,

d. Determining the various failure permutations, combinations, and system interactions, and

e. Performing the necessary calculations and data presentations.

In a dual mode transportation system, vehicles are capable of operating on a conventional street in a manual mode, and also, on specially constructed guideways in a completed automated mode.

In the manual mode, a driver will operate the vehicle in suburban residential or business districts. These surface routes will serve as collector lines and will feed into access stations. There, the driver will leave the bus and the vehicle will be placed in the automatic mode. In this mode, the mini-bus will be routed on completely automatic guideways through the heavier traveled urban corridors and the central business district.

This combination of manual and automatic operation will permit flexible routing and distribution capable of changing to suit daily or seasonal variations in passenger demand throughout an urban area. The systems also envision demand-responsive operations for nearly direct point-to-point routing.

Phase I of the Dual Mode Transit System development program will cover concept and system design with special attention being paid to improving the quality of transportation while minimizing initial capital investment, installation time and operating costs. This part of the program is expected to be completed within nine months.

Phase II will consist of construction, operational testing, and evaluation of prototypes at DOT's High Speed Test Center at Pueblo, Colorado. Phase III is expected to bring dual mode systems into revenue service in cities by 1980.

In order for the contractor to scope the dual mode system, a hypothetical Phase III scenario was provided during Phase I. It consisted of six two-way guideway corridors with nine or ten stations on each one serving a central business district (CBD) composed of approximately twenty miles of guideway and twenty stations. The system is supposed to satisfy a demand of 30,000 trip requests per hour with a nominal of 5,000 and a maximum of 10,000 per corridor. Figure 1 illustrates the scenario. The problem is to determine an availability figure of merit for this scenario during the design phase, (Phase I).

An availability analysis (1) is usually performed during the design stages of a program before any system experience has been gained. The definition most commonly used is stated as: (1)

$$\text{Availability A (so-called "steady state")} = \frac{\text{MTBF}}{\text{MTBF} + \text{MTTR}}$$

where MTBF is mean time between failure, and MTTR is mean time to repair, a measure of the effectiveness of emergency maintenance. It is assumed that all failures are random.

MTBF must be figured on the basis of a fleet of vehicles. If each vehicle has, for example, a 1000 hour MTBF, and there are 100 vehicles, a system failure could be expected every 10 hours on the average. If each one took .5 hours to repair, and each one stopped the system cold, system availability would be

$$A = \frac{1000/100}{1000/100 + .5} = .952$$

In an operating system, availability, as measured by experience is usually defined as

$$A = \frac{\text{Operating Time}}{\text{Operating Time} + \text{Down Time}}$$

In the above example, with a working day 24 hours long and one failure each 10 hours, taking .5 hours to fix,

$$A = \frac{24}{24 + 1.2} = .952$$

Clearly, if down-time or repair-time can be minimized, or if the failed vehicle can quickly be removed from the system so that it does not become an obstruction, availability can be raised. If

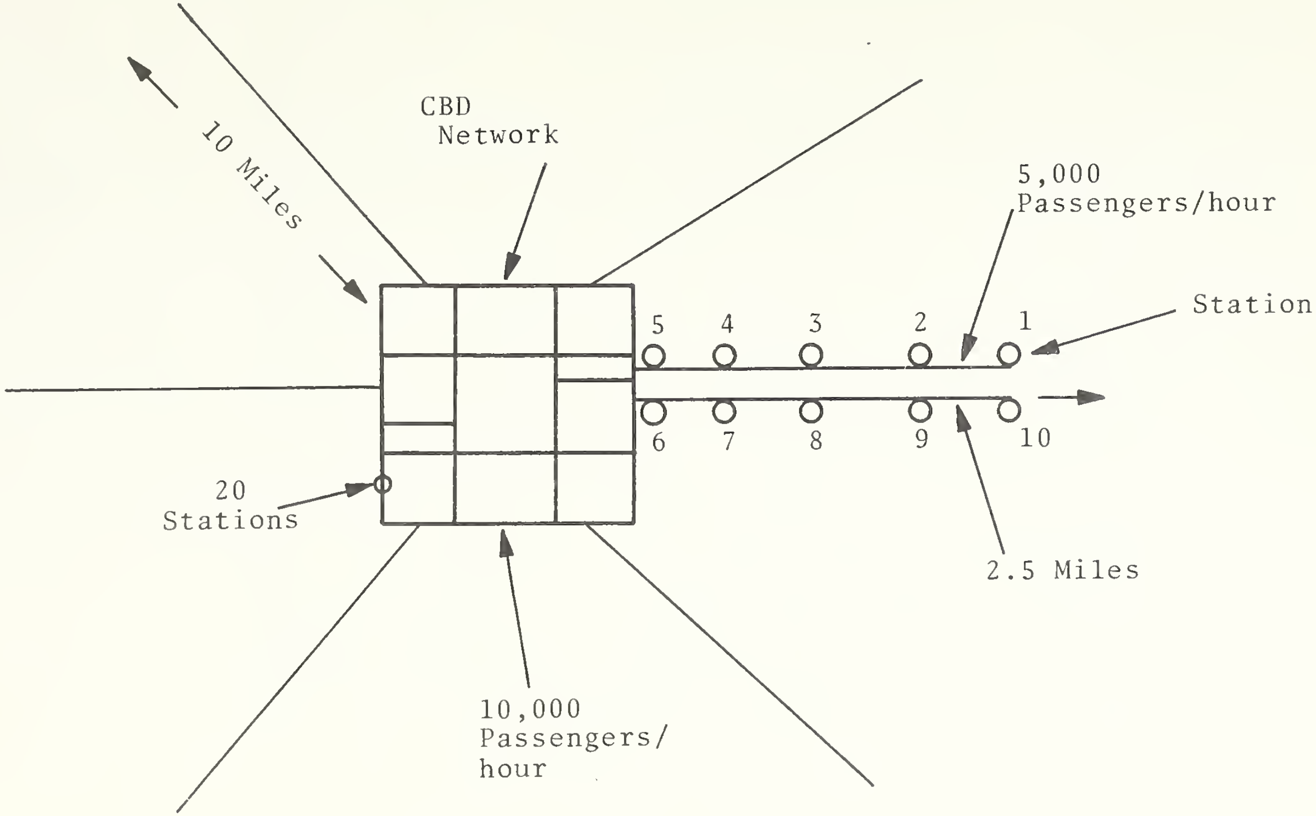


Figure 1. Phase III Scenario

the fault in the example above could be cleared in .1 hour,

$$A = \frac{24}{24 + .24} = .99$$

There are, therefore, many ways of increasing availability.

a. Increase the MTBF of the system to reduce outages. Increasing the inherent reliability of the vehicles or providing preventive maintenance during non-operating hours will have the effect desired.

b. Decrease the time to repair of on-line vehicles.

c. Design the system so that failed vehicles do not shut down the whole system. Rapid removal of the failed vehicle, bypassing an obstructed section of guideway, and similar methods can keep a system from being shut down as the result of one failure. Vehicles can also be designed with redundancy in their electronics so that in most instances they will "fail operational" rather than stop.

In practice, of course, all these things should be done to whatever extent possible.

In Phase I of the DMTS program, a "steady state" analysis based on vehicle availability will be sufficient. However, it is anticipated that a dynamic analysis will be performed in Phase II after a network computer simulation program is developed. It will address the question of passenger availability. This report describes the procedures to be used in the availability analyses during Phase I.

2. PROCEDURES (PHASE I)

The procedures presented herein define a method of evaluating the effects of failures in a complex dual mode system based on a "worst" case steady state analysis. The computed result is a figure of merit and not an absolute prediction with associated confidence levels of system availability. The advantage of this approach is that it avoids the use of a dynamic network traffic flow simulation which was not available during Phase I of the DMTS Program.

In most cases, the reliability of a DMTS can be represented by a series chain probability of its major subsystems. In actuality, each of the three contractors defined their major subsystems according to their system specification. However, for illustration purposes, a simplified subdivision is presented in Figure 2. (2) This figure shows three major hardware subsystems of the DMTS along with some of their related software functions. The system reliability, RS, can be determined by multiplying the reliability estimate of subsystems A, B, and C as follows:

$$RS = R\,A \cdot R\,B \cdot R\,C$$

A system failure rate λ S is derived by adding the failure rates of the component elements.

$$\lambda S = \lambda A + \lambda B + \lambda C$$

The individual elements or components in each major subsystem must be grouped according to a common classification such as computers.

Each particular element of each group must be individually identifiable and traceable to the subsystem(s) in which it operates. A failure effect analysis then determines if the subsystem function which has been designated as a failure will cause vehicle delay(s). If delays do occur, then the extent of them must be determined by using appropriate mean time to repair (MTTR) values.

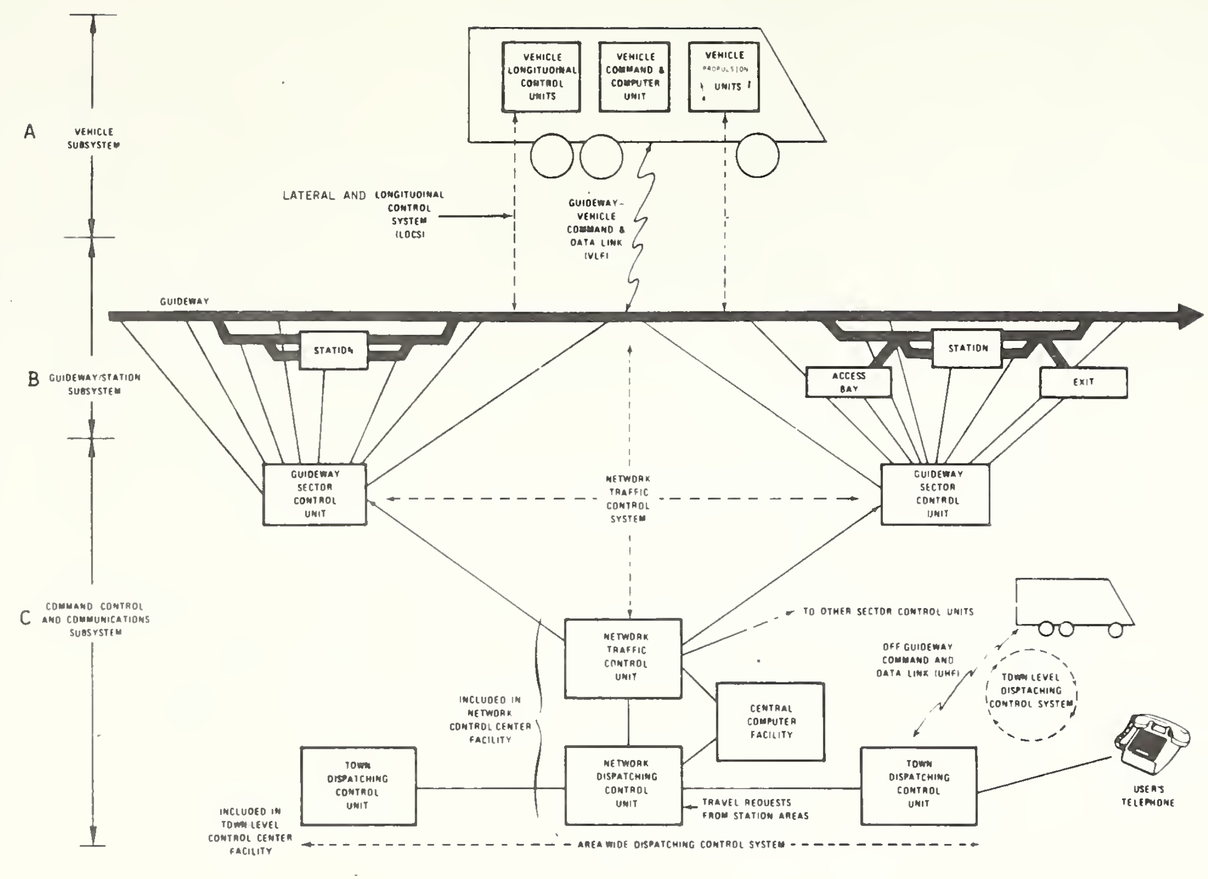


Figure 2. Dual Mode Transit Subsystems

The Monte Carlo technique is used to determine:

a. Which group of elements fail,

b. Which individual elements fail, and

c. Where on or off the guideway the delays occur (streets, guideway, station berths, etc.)

To use this method, several assumptions are implied.

a. Failure rates of all component elements are derivable and are constant; that is, failures occur randomly and are not due to design or manufacturing defects or wearout.

b. The reliability function of the total system, with maintenance, is exponential and can be expressed as $R = e^{-\lambda_s t}$, where λ_s is the system failure rate, as derived by summing the failure rates of all the system component elements, and $\underline{t}$ is the time at which reliability is measured.

3. PROCEDURES

The following procedures were recommended to the contractors for calculating a system availability figure of merit for the Phase III scenario. The examples used in these procedures are taken from the Phase III scenario. They are not to be construed as being all inclusive and definitely have to be expanded in accordance with each DMTS. The procedures consist of:

a. Dividing the system into similar kinds of major hardware and software subsystems and components as determined from its functional characteristics,

b. Determining the number of vehicles per section based on speed, percentage of vehicle/guideway occupancy, and a steady state passenger seated flow rate,

c. Conducting an appropriate FMEA based on the system design, reliability, maintainability, and safety practices,

d. Determining the various failure permutations, combinations, and system interactions, and

e. Performing the necessary calculations and data presentations.

3.1 SUBSYSTEMS AND MAJOR COMPONENTS

The DMTS specification document contains the functional definitions of the system objectives and identifies associated hardware and software requirements. The hardware examples selected for illustration in this paper were chosen because they related to certain basic assumptions that needed to be clarified before any analyses could begin. The following are four such components.

a. Guideway sections,

b. Stations,

c. Computers,

d. Merge/demerge sections.

3.1.1 Guideway Sections

Figure 3 states the approximate number of/and related assumptions to be used for each type of guideway sector as given in the Phase III scenario. There are six ten-mile two-way corridor containing eight 2 1/2-mile long Number 1 type guideway sectors as shown in Figure 3 (i.e. four sectors each way).

3.1.2 Stations

Two types of stations can be defined for the Phase III scenario:

a. Entrance/egress used as vehicle entrance and departure exits on the corridor and CBD guideway, and

b. Stop only/transfer used only by the CBD.

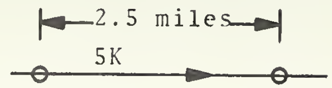
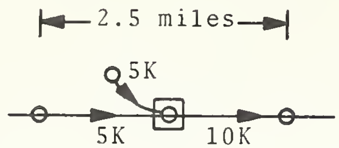
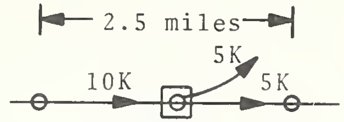
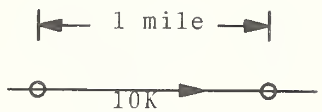
   1. There are only seventy entrance/egress stations: sixty on the guideway corridors and eight in the CBD. Each one of these sixty-eight has a passenger flow of 2,000 per hour in each direction. There are two more stations in the CBD that have a passenger flow of 5,000 per hour in each direction.

   2. There are ten stop only/transfer stations in the CBD that have a passenger flow of 2,000 passenger per hour in each direction. The passenger flow rate should be converted into vehicles at one hundred percent seated occupancy and no allowances made for standees. Stations may contain parallel or series berths or a combination of both depending on the design selected.

3.1.3 Computers

The type of computer used in each application will depend on the function to be performed, data rates, message formats, etc., that are particular to the system design. The following classifications can be used as applicable:

GUIDEWAY SECTORS

Type Number	Possible Number of	Description	Assumptions
1	48		60 mph
2	20		30 mph Merge Point at Corridor and CBD Network Intersection
3	20		30 mph Demerge Point at Corridor and CBD
4	20	 In CBD	30 mph

0 = Station

K = Passenger flow/hour in 1000's

☐ = Points

Figure 3. Guideway Sectors

a. Wayside
b. Sector
c. Central

The number of/and configuration of components is to be determined from the system design.

3.1.4 Merge/Demerge Points

There are 80 merge and 80 demerge points shown in Figures 4 and 5 located on acceleration and deceleration ramps associated with the 80 stations mentioned in item b. above.

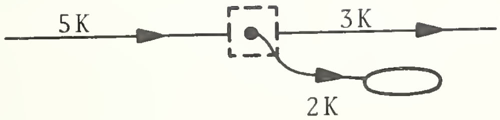


Figure 4. Demerge Point

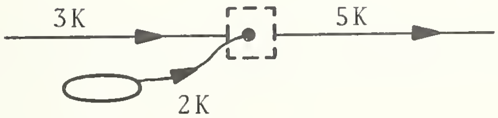


Figure 5. Merge Point

3.2 NUMBER OF VEHICLES

To determine the number of vehicles per hour required to make the seated passenger flow for all of the above cases, the following items must be considered:

a. Vehicle capacity,

b. The headway analyses,

c. Slot occupancy percentage.

This allows for merging conditions, and

d. The required seated passenger flow per hour.

A computer program for determining guideway sector utilization is found in Reference 2.

3.3 FMEA (FAILURE MODE AND EFFECT ANALYSES)

Upon completion of the procedures stated in Section 3.1 and 3.2 above, a failure mode and effect analysis should then be conducted for the major subsystems and components. For each failure mode, appropriate vehicle delay times can be determined. The sum total of all vehicle delays attributed to that particular failure mode including those vehicles affected in other guideway sectors must be calculated. The FMEA should classify failures with respect to:

a. Hazard levels for safety considerations,

b. Catastrophic system shut down, and

c. Servicibility

   1. Corrective action that can occur within a given time interval and thus avoid a vehicle delay.

   2. Corrective action that can only occur beyond a given time interval, thus resulting in a vehicle delay.

A typical fault tree analysis as used by C. Watt of Transportation Systems Center in a system safety study is shown in Figure 6.

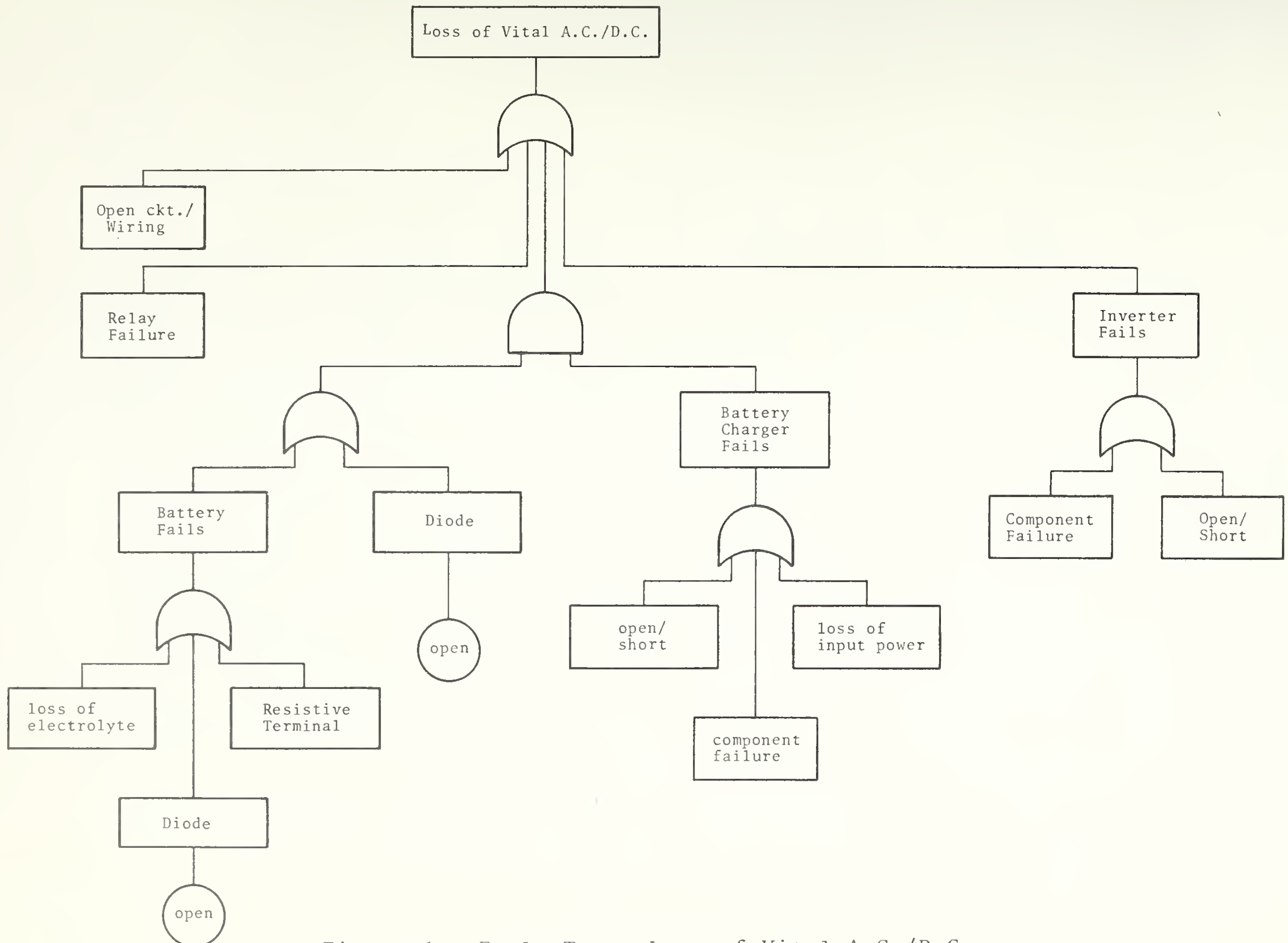


Figure 6. Fault Tree, Loss of Vital A.C./D.C.

3.4 FAILURE MODE DETERMINATION

A probability estimate for the occurrence of each failure mode can be derived from a reliability failure rate apportionment analyses. A maintainability analyses should also be performed to determine the MTTR for each failure mode.

The Monte Carlo technique should then be employed to determine which subsystem failed, at what time, and where in the network vehicle delays occurred. The procedure is given as follows:

a. Subsystems and components must be related to the guideway network in order to determine where in the network a delay occurs. For example, guideway sectors and associated peripheral subsystems and components should be assigned to corridors by number. For each type of guideway sector (including berths in the stations) vehicle positions should also be numbered.

b. Failure rates for the major subsystems and components can be calculated from the reliability apportionment analyses stated above. The relative frequency of a failure of a particular subsystem with respect to other types of subsystems can be determined.

c. The Monte Carlo technique can utilize the relative frequency of occurrence to determine which subsystem failed. A computer can easily perform this task.

For the DMTS, a double Monte Carlo procedure could be used to designate component failures. The first procedure would select which of the major subsystems the failure(s) occurred in and the second would assign component failures within subsystems. Consequently, two frequency distribution of events are required.

For the major subsystem distribution, there are eight event categories as follows. Seven define the probability of events A, B, and C failing while one gives the probability of no failures occurring.

1. 1-RA — A. Failing
2. 1-RB — B. Failing
3. 1-RC — C. Failing
4. (1-RA) (1-RB) — A and B. Failing
5. (1-RA) (1-RC) — A and C. Failing
6. (1-RB) (1-RC) — B and C. Failing
7. (1-RA) (1-RB) (1-RC) — A, B, and C. Failing
8. The probability of no failures occurring, which is given by: 1 - the sum of categories 1 through 8.

The major subsystem frequency distribution can be derived from the probabilities associated with these events. Now the components within each subsystem can be arranged accordingly to derive a similar frequency distribution for major components. With the aid of a random number generator, events can be iterately selected based on an appropriate time interval derived from failure rate data. The entire procedure can be incorporated into a computer program.

In a similar manner, the Monte Carlo technique can also be used to assign corridor guideway sections and vehicle positions to those failure modes that cause vehicle delays.

The effect of each vehicle delay can then be analyzed manually and appropriate delay times calculated.

3.5 CALCULATIONS AND DATA PRESENTATION

Failure modes can be grouped or classified according to vehicle delay times and a probability of occurrence can be calculated for each classification. A graph of this data can be drawn as shown in Figure 7.

The availability figure of merit can be calculated by:

$$AV = 1 - \frac{\Sigma D}{\Sigma D + \Sigma O}$$

where: D = vehicle delay times

O = vehicle operating times

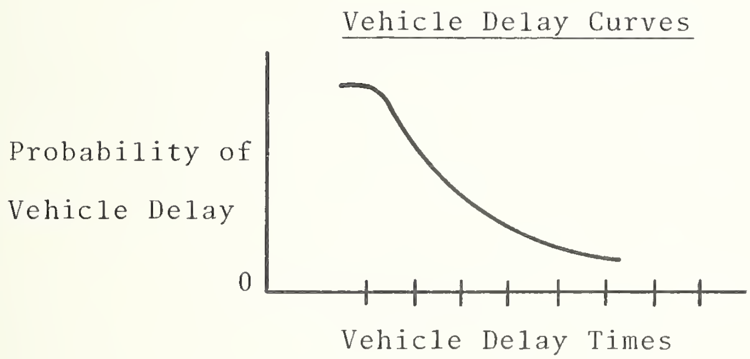


Figure 7. Vehicle Relay Curve

3.5.1 System Duty Cycle

The operating cycle per day shall be:

a. 5,000 passenger/hr/corridor guideway sector for six hours per day,

b. 1,000 passenger/hr/corridor guideway sector for eighteen hours per day,

c. 10,000 passenger/hr/CBD guideway sector for six hours per day,

d. 2,000 passenger/hr/CBD guideway sector for eighteen hours per day.

The analyses should cover a seven-day week for three consecutive years.

3.5.2 Off-Guideway Considerations

In order to consider off-guideway failure modes for the Phase III scenario, the following assumptions are given:

a. The passenger flow rates associated with each entrance/ egress station (70 of them) is related to an appropriate Dial-A-Bus Zone of ten miles. Six equally spaced stops are made per zone.

b. The vehicle street speed is fifteen miles per hour for both Dial-A-Bus and by-pass guideway operations.

4. CONCLUSIONS

Apparently, an availability procedure as extensive as the one outlined above has never before been conducted for a ground transportation system of the magnitude and complexity of dual mode. Early results from the three dual mode contractors indicate that the availability effort has proven fruitful in the concept developing stage by a) integrating the reliability, maintainability, and safety analytical tasks, b) providing a design criteria against which subsystem designs can be realistically evaluated in view of the overall system requirements, and c) providing a criteria for evaluating the effects of abnormal operating procedures.

Detailed reports giving the results of the availability effort will be forthcoming at the end of the Phase I Dual Mode Program.

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2. Charles R. Toye, Accumulative Probability Model for Automated Network Traffic Analyses. Report No. DOT-TSC-OST-72-30, U.S. Department of Transportation, Transportation Systems Center, Cambridge MA, October 1972.