Availability Analysis of Dual-Mode Systems

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The analytical procedures presented 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. The availability calculation is 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, and corrective action times required to avoid vehicle delays.

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. In September 1973, the Urban Mass Transportation Administration awarded three contracts for the design phase of a dual-mode transit system (DMTS) development program. The objective of this dual-mode program is to combine the best automated transit such as the personal rapid transit (PRT) system in Morgantown, West Virginia, with the best aspects of modern bus technology.

This report discusses the availability procedures that were given to the contractors who were selected to participate in phase 1 of the UMTA dual-mode program. The procedures are 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 concept development or design phase of a system. In a ground transportation 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 1 of the dual-mode program, the emphasis is on vehicle delays derived from a worst case steady-state analysis. This avoids the use of a dynamic network traffic flow simulation, which is required for the computation of passenger delays and is deferred until phase 2 of the program.

The approach taken encompasses fault tree and failure mode and effect analyses (FMEA). The novel aspect of this approach is the use of the Monte Carlo technique to determine the physical location of failed vehicles. The requirements of phase 3 are discussed with respect to types of stations, guideway sectors, passenger flow, and network configurations.

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 operates the vehicle in suburban residential or business districts. These surface routes serve as collector lines and feed into access stations. There, the driver leaves the bus, and the vehicle is placed in the automatic mode. In this mode, the minibus is routed on completely automatic guideways through the heavier traveled urban corridors and the central business district. This combination of manual and automatic operation permits flexible routing and distribution capable of changing to suit daily or seasonal variations in passenger demand throughout an urban area. The system also permits demand-responsive operations for nearly direct point-to-point routing.

Phase 1 of the dual-mode development program covers concept and system design with special attention 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 9 months. Phase 2 consists of construction, operational testing, and evaluation of prototypes at the U.S. Department of Transportation test center at Pueblo, Colorado. Phase 3 is expected to bring dual-mode systems into revenue service in cities by 1980.

A hypothetical phase-3 installation was provided as a basis for the phase-1 work. Each corridor has nine or ten stations, serves a central business district (CBD), and has approximately 32.2 km (20 miles) of guideway and 20 stations. The system is supposed to satisfy a demand of 30 000 trip requests per hour with a nominal of 5000 and a maximum of 10 000 per corridor. Figure 1 shows the installation. The problem is to determine an availability figure of merit for this system during the design phase.

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

$$\text{Availability A (so-called steady state)} = \frac{\text{MTBF}}{\text{MTBF} + \text{MTTR}} \qquad (1)$$

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

MTBF must be figured on the basis of a fleet of vehicles. If there are 100 vehicles and each one has, for example, a 1000-h MTBF, a system failure could be expected every 10 h on the average. If each one took 0.5 h to repair and each one stopped the entire system, system availability would be

$$A = \frac{1000/100}{1000/100 + 0.5} = 0.952 \qquad (2)$$

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

$$A = \frac{\text{operating time}}{\text{operating time} + \text{down time}} \qquad (3)$$

For a working day 24 h long and one failure each 10 h that takes 0.5 h to fix,

$$A = \frac{24}{24 + 1.2} = 0.952 \qquad (4)$$

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 the fault can be cleared in 0.1 h,

$$A = \frac{24}{24 + 0.24} = 0.99 \qquad (5)$$

There are, therefore, many ways of increasing availability:

1. Increase the MTBF of the system to reduce outages (increasing the inherent reliability of the vehicles or providing preventive maintenance during nonoperating hours will have the effect desired),
2. Decrease the time to repair on-line vehicles, and
3. 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 1 of the DMTS program, a steady-state analysis based on vehicle availability is sufficient. However, a dynamic analysis is to be performed in phase 2 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 1.

PROCEDURES

The procedures presented here 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 that was not available during phase 1 of the DMTS program.

In most cases, the reliability of a DMTS can be represented by a series chain probability of its major subsystems. Each of the three UMTA contractors defined their major subsystems according to their system specification, but for illustration purposes a simplified subdivision is shown in Figure 2 (2). Shown are the three major hardware subsystems of the DMTS and 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:

$$RS = RA \cdot RB \cdot RC \qquad (6)$$

A system failure rate, λS, is derived by adding the failure rates of the component elements.

$$\lambda S = \lambda A + \lambda B + \lambda C \qquad (7)$$

The individual elements or components in each major subsystem must be grouped according to a common classification. Each particular element of each group must be individually identifiable and traceable to the subsystem in which it operates. A failure effect analysis then determines whether the subsystem function that has been designated as a failure will cause vehicle delay. If delays do occur, then their extent must be determined by using appropriate MTTR values. The Monte Carlo technique is used to determine which group of elements fail, which individual elements fail, and where on or off the guideway the delays occur (streets, guideway, station berths). This method has the following implied assumptions:

1. 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 wear out); and
2. 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 t is the time at which reliability is measured.

The following procedures were recommended to the contractors for calculating a system availability figure of merit for phase 3:

1. Divide the system into similar kinds of major hardware and software subsystems and components as determined from its functional characteristics;
2. Determine the number of vehicles per section based on speed, percentage of vehicle and guideway occupancy, and a steady-state passenger seated flow rate;
3. Conduct an appropriate failure mode and effect analysis (FMEA) based on the system design, reliability, maintainability, and safety practices;
4. Determine the various failure permutations, combinations, and system interactions; and
5. Perform the necessary calculations and data presentations.

The examples used in these procedures are taken from the phase-3 installation and are not to be construed as being all inclusive; they have to be expanded in accordance with each DMTS.

Subsystems and Major Components

The DMTS specification document contains the functional definitions of the system objectives and identifies associated hardware and software requirements. The following 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: guideway sections, stations, computers, and merge and demerge sections.

The approximate number of and related assumptions for each type of phase-3 guideway sections are as follows:

Type	Possible Number	Assumption
1	48	96.6 km/h
2	20	48.3 km/h; merge point at corridor and CBD network intersection
3	20	48.3 km/h; demerge at corridor and CBD
4	20	48.3 km/h

There are six 16.1-km (10-mile) two-way corridors containing eight 4-km-long (2.5-mile) type 1 guideway sections as shown in Figure 3 (i.e., four sections each way).

The two types of stations defined for phase 3 are (a) entrance and egress stations used as vehicle entrance and departure exits on the corridor and CBD guideway, and (b) stop only and transfer stations used only in the CBD. There are only 70 entrance and egress stations: 60 are in the guideway corridors and 8 are in the CBD. Each one of these 68 stations has a flow of 2000 passengers/h in each direction. Two more stations in the CBD have a flow of 5000 passengers/h in each direction. There are 10 stop only and transfer stations in the CBD that have a flow of 2000 passengers/h in each direction. The passenger flow rate is converted into vehicles at 100 percent seated occupancy; no allowances are made for standees. Stations may contain parallel or series berths or a combination of both depending on the design selected.

The type of computer used in each application depends

Figure 1. Phase-3 installation of a dual-mode transit system.

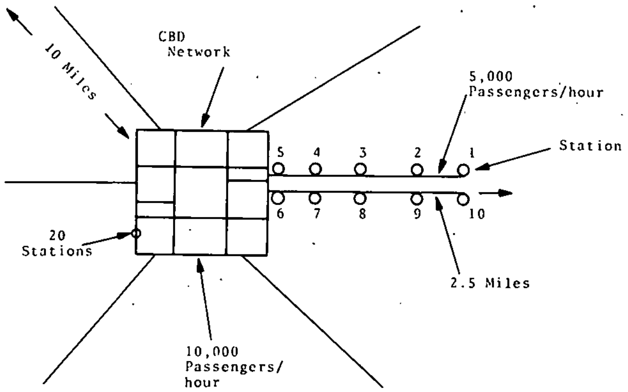


Figure 2. Dual-mode transit subsystems.

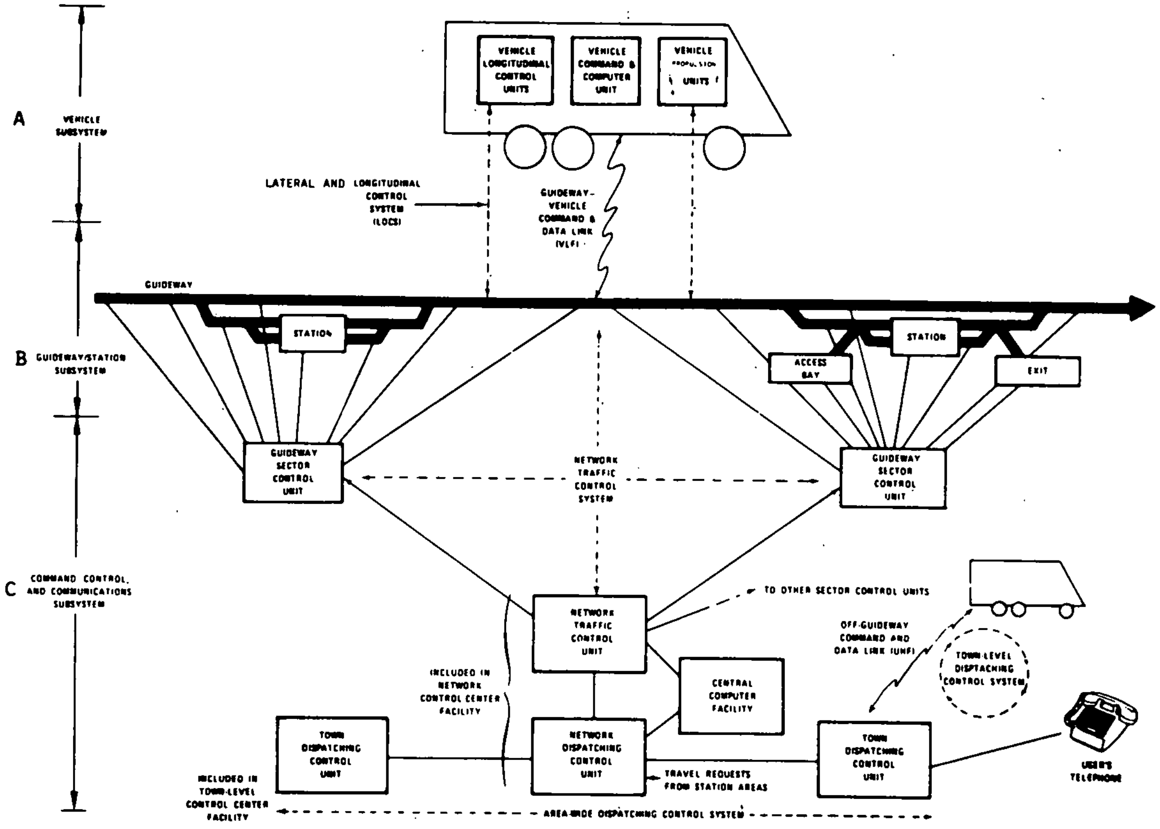


Figure 3. Guideway sections.

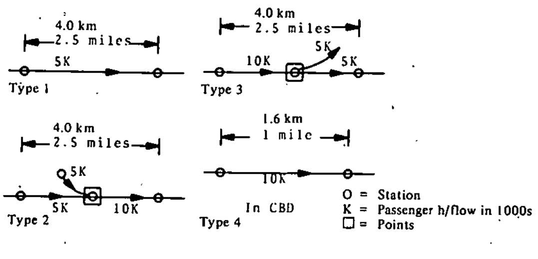


Figure 4. Demerge and merge points.

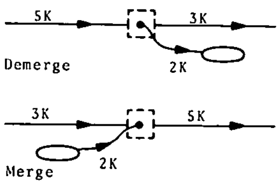


Figure 5. Fault tree.

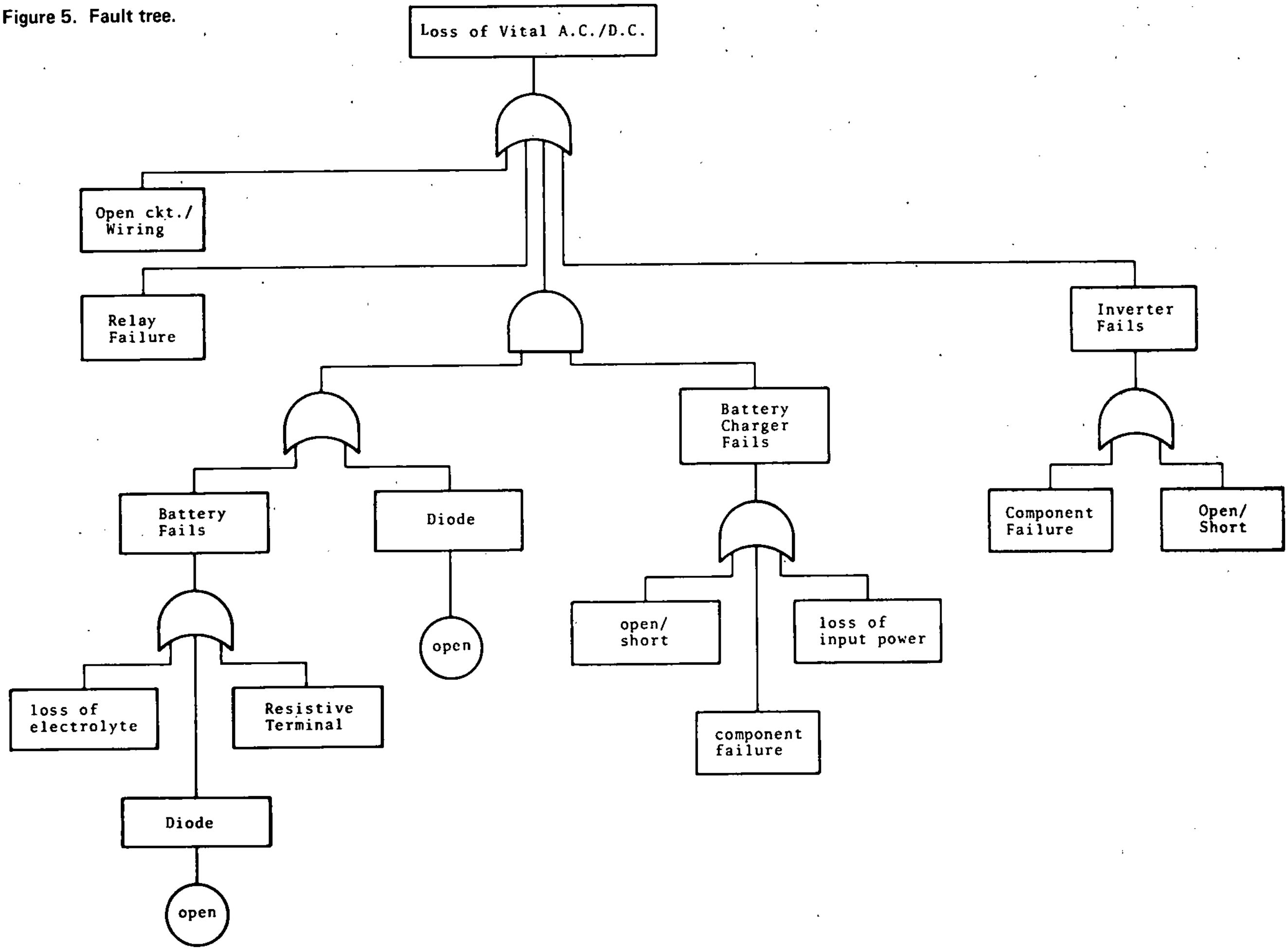
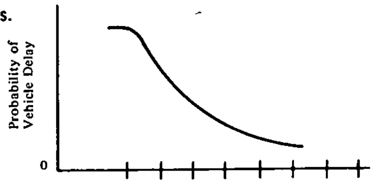


Figure 6. Vehicle delay curves.



on the function to be performed, data rates, and message formats peculiar to the system design. The classifications to be used as applicable are wayside, sector, and central (the number of and configuration of components is to be determined from the system design).

There are 80 merge and 80 demerge points (Figure 4) located on acceleration and deceleration ramps associated with the 80 stations mentioned above.

Number of Vehicles

In the determination of the number of vehicles per hour required to make the seated passenger flow for all of the above cases, the following items are considered: vehicle capacity, headway analyses, slot occupancy percentage (this allows for merging conditions), and required seated passenger flow per hour. A computer program for determining guideway section use is given in another report (2).

Failure Mode and Effect Analyses

After the above procedures have been carried out, an FMEA is conducted for the major subsystems and components. For each failure mode, appropriate vehicle delay times are determined. The sum of all vehicle delays attributed to that particular failure mode including those vehicles affected in other guideway sections is calculated. The FMEA should classify failures with respect to

1. Hazard levels for safety considerations,
2. Catastrophic system shutdown, and
3. Serviceability [corrective action that can (a) occur within a given time interval and thus avoid a vehicle delay or (b) only occur beyond a given time interval, thus resulting in a vehicle delay].

A typical fault tree analysis used in a system safety study at the Transportation Systems Center is shown in Figure 5.

Failure Mode Determination

A probability estimate for the occurrence of each failure mode is derived from a reliability failure rate apportionment analysis. A maintainability analysis is performed to determine the MTTR for each failure mode. The Monte Carlo technique is then used to determine which subsystem failed and when and where in the network vehicle delays occurred. The procedure is as follows.

1. Subsystems and components are related to the guideway network to determine where in the network a delay occurs. For example, guideway sections and associated peripheral subsystems and components are assigned to corridors by number. For each type of guideway section (including berths in the stations), vehicle positions are also numbered.
2. Failure rates for the major subsystems and components are 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 is determined.
3. The Monte Carlo technique uses the relative frequency of occurrence to determine which subsystem failed. A computer performs this task.

For the DMTS, a double Monte Carlo procedure is used to designate component failures. The first procedure selects the major subsystems in which failure occurred and the second assigns component failures within subsystems. Consequently, two frequency distributions 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, and one gives the probability of no failures occurring):

Category	Event Failing
1 - RA	A
1 - RB	B
1 - RC	C
(1 - RA) (1 - RB)	A and B
(1 - RA) (1 - RC)	A and C
(1 - RB) (1 - RC)	B and C
(1 - RA) (1 - RB) (1 - RC)	A, B, and C
1 - (sum of categories 1 through 8)	None

The major subsystem frequency distribution is derived from the probabilities associated with these events. The components within each subsystem are then arranged accordingly to derive a similar frequency distribution for major components. A random number generator is used to select events iteratively 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 is also used to assign corridor guideway sections and vehicle positions to those failure modes that cause vehicle delays. The effect of each vehicle delay is then analyzed manually, and appropriate delay times are calculated.

Calculations and Data Presentation

Failure modes are grouped or classified according to vehicle delay times, and a probability of occurrence is calculated for each classification. Figure 6 shows how these data can be plotted. The availability figure of merit is calculated by

$$AV = 1 - \frac{\sum D}{\sum D + \sum O} \qquad (8)$$

where

D = vehicle delay times, and
O = vehicle operating times.

The operating cycle per day is (a) 5000 passengers/h/corridor guideway section for 6 h/d, (b) 1000 passengers/h/corridor guideway section for 18 h/d, (c) 10 000 passengers/h/CBD guideway section for 6 h/d, and (d) 2000 passengers/h/CBD guideway section for 18 h/d. The analyses will cover a 7-d week for 3 consecutive years.

The following assumptions are used in considerations of off-guideway failure modes for phase 3.

1. The passenger flow rates associated with each of the 70 entrance and egress stations are related to an appropriate dial-a-bus zone of 16.1 km (10 miles). Six equally spaced stops are made per zone.
2. The vehicle street speed is 24 km/h (15 mph) for both dial-a-bus and bypass guideway operations.

CONCLUSIONS

An availability procedure as extensive as the one outlined above has apparently 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 proved fruitful in the concept developing stage by (a) integrating the reliability, maintainability, and safety analytical tasks; (b) providing design criteria against which subsystem designs can be realistically evaluated in view of the overall system requirements; and (c) providing criteria for evaluating the effects of abnormal operating procedures.

REFERENCES

1. UMTA Dual-Mode Transit System. General Motors Technical Center, Warren, Mich., June 1973.
2. C. R. Toye. Accumulative Probability Model for Automated Network Traffic Analyses. Transportation Systems Center, U.S. Department of Transportation, Cambridge, Mass., Rept. DOT-TSC-OST-72-30, Oct. 1972.