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AUTOMATED GUIDEWAY TRANSIT SERVICE AVAILABILITY WORKSHOP

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Transportation Systems Center
Kendall Square
Cambridge MA 02142



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FINAL REPORT

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16. Abstract A workshop was conducted by the Transportation Systems Center to discuss, from a number of viewpoints, the meaning, specification, and measurement of service availability in automated guideway transit (AGT) systems. The makeup of the workshop ensured that the widest spectrum of informed opinion was brought to bear on the questions involved. These included definitions of service availability; the way it is being, or should be, specified, predicted, and measured; and how, for a transit system, such a system-level parameter can be translated into meaningful and measurable hardware requirements for designers and builders. Four panels of participants experienced in this area discussed these questions; the texts of their remarks are presented in this report, with only minor editing. In addition, much discussion was generated; this is also presented in the report, with only enough editing to provide continuity and clarity. The discussions illustrated clearly the wide spectrum of meanings currently given to the term "service availability." The positions taken by representatives of the various portions of the transit industry - properties, designers, researchers, and manufacturers - showed the variety of ways in which system performance is specified and evaluated today, and the reasons for such a variety.					
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PREFACE

The Service Availability Workshop, sponsored by the Urban Mass Transportation Administration (UMTA) and arranged by the Transportation Systems Center (TSC), Cambridge, Massachusetts, was held at the Andover Rolling Green Motor Inn, Andover, Massachusetts on October 6, 7 and 8, 1976. The workshop consisted of four panel sessions, which included presentation of papers, followed by question-and-answer periods relevant to the paper presentations. These activities were participated in by panel members and invited guests for the furthering of understanding and the potential future implementation of the following objectives:

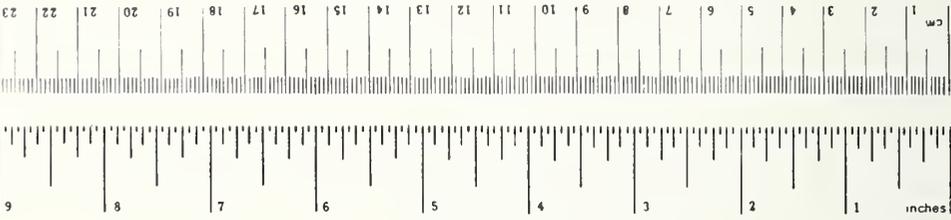
1. Establish, define, and document measures for ensuring service availability in automated guideway transit and other transit systems.

2. Identify analytical methods for calculating these measures in terms of reliability, maintainability, topology, and/or passenger reaction in transit networks.

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			
m 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



Approximate Conversions from Metric Measures

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

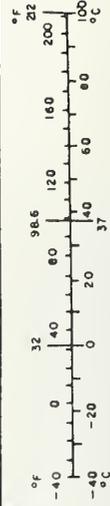


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INTRODUCTION AND SUMMARY

As part of an ongoing program of Automated Guideway Transit Technology improvement funded by the Urban Mass Transportation Administration (UMTA), this workshop presented, in four panel sessions, a wide spectrum of informed opinion on how to specify, predict, design and measure the effectiveness of automated transit systems.

No specific conclusions were expected from this meeting. Instead, the entire subject was thoroughly aired, and various approaches were presented and discussed by the panels and the audience.

Panel 1 reviewed definitions of service availability. Mr. W. J. Roesler, of Johns Hopkins University, presented several definitions used in the UMTA Dual Mode Design Study and AGRT (Advanced Group Rapid Transit) Programs. Mr. C. O. Buhlman, of the Maryland Mass Transit Administration, presented a rapid transit viewpoint. The position of APTA (American Public Transit Association) on service availability was stated by Mr. D. Gardner, of the Southern California Rapid Transit District. Cost versus service availability was discussed by Mr. F. C. Smith, of Frank C. Smith Associates. Mr. H. L. Tucker, of DOT (Department of Transportation), provided a review of the AGRT Program, and Dr. D. Heimann, of TSC (Transportation Systems Center), presented the final paper of the panel, an availability analysis of a rail rapid transit system. In general, the concept of specifying maximum acceptable passenger delays resulting from equipment failures seemed to emerge from the papers and the discussions as the most

meaningful, if not the most practical, measure of service availability.

Panel 2 presented the experiences of a number of real-life transit operators, which included a conventional manually operated rail rapid transit system, an automated rapid transit system, AGT (Automated Guideway Transit) systems, and a high-speed semi-automated system. The results of these experiences appeared to stress the need for easily understood and measured indices of system performance which can be routinely obtained from day-to-day operation. The AIRTRANS experience was presented by Mr. D. Ochsner of Battelle Columbus Laboratories, and the SeaTac (Seattle-Tacoma) experience by Mr. M. Bitts. Mr. J. King, of BART (Bay Area Rapid Transit), discussed that system's reliability and availability data systems and methods of evaluation. Mr. K. Bisset, of the Chicago Transit Authority (CTA), discussed the CTA attitudes, and Mr. J. W. Vigrass of PATCO (Port Authority Transit Corporation, New Jersey) provided information on methods adopted by the PATCO system.

Panel 3 reviewed several mathematical modeling methods used for system analysis; any one, or all of them, could be used during system conception and specification to describe and define system response to malfunctions of various kinds. Life cycle costs versus reliability allocations were discussed by Dr. J. E. Anderson, of the University of Minnesota. Dr. W. C. Womack, of the Otis Elevator Company, presented an approach to AGT dependability analysis, and Mr. Tucker, in his second presentation, generated a method of availability analysis for AGT

systems. Mr. R. N. Oglesby, of General Motors Corporation, discussed availability simulation, and Mr. Roesler, in a second presentation, dealt with a trip dependability model for AGRT networks. The next paper was presented by Dr. L. Doyon, of Northeastern University. Dr. Doyon showed how system reliability and maintainability can be modeled by use of Markov state-transition diagrams. The final paper of this panel was presented by Dr. E. Diamant, of DeLeuw, Cather & Company. Dr. Diamant's paper involved system aspects of service availability.

Panel 4 was made up of representatives of the equipment designers and builders. These people stressed the need for specification requirements that can be easily translated into hardware reliability and maintainability parameters for use during design and test.

By the end of the workshop, no formally articulated consensus had been derived, but the feeling was expressed by several people, from the panel speakers as well as from the audience, that several indices of system and service availability may be needed. The requirements of a performance specification are oriented toward operation of the system and the delivery of satisfactory passenger service. Here, passenger delay measures are effective ways of defining how good a system must be. The designers and manufacturers of equipment, however, require measures that can be interpreted as constraints on the reliability of component parts and the ease of maintenance of electromechanical designs. In addition, the buyers and sellers must agree on test measures which will allow unambiguous system acceptance or rejection, and will eventually permit effective operational monitoring.

During FY'77 and FY'78 UMTA has funded serveral studies seeking to develop common approaches to service availability, which, as indicated by this workshop, were urgently needed.

PANEL 1
SERVICE AVAILABILITY DEFINITIONS

PANEL 1
SERVICE AVAILABILITY DEFINITIONS

The first session of the workshop proceedings began with host Mr. C.W. Watt introducing Dr. Duncan MacKinnon as chairman for Panel 1. Dr. MacKinnon is Chief of the Advanced Development Program in the Office of Technical Development and Deployment of the Urban Mass Transportation Administration. He received a BS degree in Electrical Engineering from the University of Toronto in 1961 and a doctorate in Electrical Engineering from Cornell University in 1966, and has served as Chief of the Advanced Development Branch since 1972.

Following Mr. Watt's introduction, Dr. MacKinnon commented briefly on service availability of transit systems, and then called on Mr. W. J. Roesler, a scientist from Johns Hopkins University, to speak. Mr. Roesler responded with the first of a series of papers presented at this panel session.

The complete proceedings of Panel 1 are described in the following text, beginning with Dr. MacKinnon's introductory comments and Mr. Roesler's paper mentioned above. The paper is followed by questions and answers, and by comments on its significance. This sequence is repeated for the other paper presentations until the entire panel proceedings have been covered.

Note: The reader is advised that the contents of the respective papers are essentially as delivered by the authors; however, the transcribed statements, questions and answers, and comments attributable to different panel members and the audience have been edited. The editing does not alter the original meaning of the transcribed material.

Dr. MacKinnon:

I welcome you all to Panel 1 of the Urban Mass Transportation Administration's Workshop on Automated Guideway Transit Service Availability. Service availability is a highly

appropriate topic at this time with automated transit systems nearing urban deployment in the Downtown People Mover (DPM) program and with a new generation of automated transit systems being developed in phase 2 of the Advanced Group Rapid Transit (AGRT) Program. Service availability may be defined as a concept which provides a measure of the consistency of a transportation service. The passenger judges service availability on the basis of the rate and travel time variations of the service provided. The operator, on the other hand, will be concerned with the impact of service consistency on ridership and the impact on operating and maintenance costs of measures required to preserve service and ridership. While most of us have a reasonably clear concept of service availability, it has proven to be a difficult idea to express quantitatively. The main objects of this workshop are: (1) to aid, define, and document service availability measures applicable to automated guideway transit and other transit systems; and (2) to identify analytical methods which can be applied to calculate the measures based on hardware, availability attributes, and the topological characteristics of transit networks. The measures and methods partly adopted for incorporation into specifications must be acceptable to both system operators and the manufacturers of systems.

The topic of this first panel session is service availability definitions. The panel will consider a variety of factors which enter into the selection and evaluation of service availability measures. The first speaker, Jerry Roesler, is a scientist at the Applied Physics Laboratory of the Johns Hopkins University. He will consider an overview of service availability definitions and analytical techniques used by system operators, systems developers, and researchers. Jerry received an MS degree in Operations Research from Johns Hopkins University in 1964, and an AB degree from Loyola College in 1956. From 1960 to 1965 he was involved in analyses of missile systems, and from 1968 to 1972 in UMTA-sponsored development of methods for managing fleets of automated

transit vehicles. Currently he's involved in the systems analysis of automated transit systems, particularly those analyses applying to the AGRT program. I'll turn this discussion over to Jerry now.

PANEL 1

PAPER 1

SERVICE AVAILABILITY IN NEW SYSTEM
DESIGNS

W. J. ROESLER

SERVICE AVAILABILITY IN NEW SYSTEM DESIGNS

W. J. ROESLER

INTRODUCTION

This paper describes briefly several of the definitions and measures pertaining to service availability which were, or are, being used by new AGT systems developments. There have been other studies, such as the Minneapolis PRT Study and the Denver Alternatives Analyses, which have addressed service availability, but these will not be discussed here. In the context of this paper, service availability will be taken to refer to transit system measures which reflect the degree of system punctuality or the degree to which a passenger can expect to arrive when planned. This measure complements the usual efficiency measure of passenger service, namely, travel speed or travel time. In the new systems literature the "service availability" concept has been called by a number of names: service reliability, trip reliability, schedule reliability, system availability, trip dependability, conveyance dependability, and, doubtless, others.

In all of these definitions the "ability" words have been used in their generic sense, not in the specific technical sense of the reliability engineering discipline.

SPECIFIC PROGRAM SERVICE AVAILABILITY

Before further discussion it would be useful to consider the specific service availability definitions used in new systems studies. Three AGT programs have been examined for these measures: (1) the Morgantown PRT Development Project; (2) the Dual Mode Design Study; and (3) the Advanced GRT Program.

Morgantown PRT

The basic figure of merit used was the conveyance dependability. Conveyance dependability is defined as the product of the probabilities that the system is ready for use at any random

point in time and that an average trip will be successfully completed. The first probability represents the classical definition of the availability of a system. The second probability represents the classical reliability, i.e., no failure for a period of time equivalent to the time for an average trip. The expression used for computing conveyance dependability was

$$D = \frac{8760 - DT}{8760} \exp \{ - t/MTBF \}$$

where

DT is the total downtime in a year
 t is the average trip time (= 5 min.)
 MTBF is the mean time between failures
 affecting travel $\left(= \frac{8760 - DT}{\text{Total Failures}} \right)$

The measure is passenger-oriented in the sense that an average trip represents a typical passenger. The primary use of the measure seems to be in the allocation of reliability and maintainability design parameters to the lower level subsystem and components. A conventional failure mode and effects analysis was used for this purpose. The measure can also be used during system operation as a service quality control index, since it does contain those operationally derived quantities, downtime and number of failures.

Dual Mode Development

The Dual Mode development program defined a system availability index A, computed by the formula

$$A = 1 - \frac{VDH}{VOH + VDH}$$

where VDH is the total hours of delay experienced by vehicles in the system

VOH is the total number of normal operating hours by vehicles.

The measure provides an equilibrium quantity, and is defined by the long-term observation of network operation. The primary purpose of this measure again appears to have been the allocation of hardware failure rates to subsystems and components by means of a failure mode and effects analysis. Implementation of a model requires that vehicle delays be determined for the various locations in the network where failures can occur. As a passenger-oriented index of service quality, interpreting the availability as the fraction of vehicle operations devoted to normal service may be somewhat more appropriate. How individual trips in a network would fare is not directly obtainable.

Advanced GRT Development

The advanced GRT development program uses a combination of the frequency of occurrence of a delay and the duration of delay as a measure of the service dependability. Simply stated, the measure defines three categories of delay, C , delimited by the length of delay incurred, and then defines the frequency of user trips allowed such delays. This can be expressed in equation form as:

$$\Pr \{D \in C_A\} = f_A$$

$$\Pr \{D \in C_B\} = f_B$$

$$\Pr \{D \in C_C\} = f_C$$

where D is the delay that a typical trip will experience. These quantities are the limits to the annual failure occurrences which a trip will experience. There is also a requirement that total annual delay experienced by the typical trip be less than a prescribed value. In the course of the AGRT development a number of models are to be developed for relating the system measure to system design parameter. It appears that the system design effort is concentrating on the hardware reliability aspects, while the urban deployability studies are concentrating on the network layout and failure management aspects. The primary use of the

measures is in developing the subsystem and component reliability requirements, i.e., in the reliability, recovery allocation process.

OBSERVATIONS

The definitions of measures of service availability all focus on the delays associated with hardware failures. The concept of delay might be equated with the current operational transit systems measure of "on time", i.e., within some designated interval of a scheduled time. The difference is partly due to the timetable-operated nature of current transit in contrast to the more demand-responsive operating policies envisioned for new systems. The measures proposed for new systems generally focused on an average trip or a network measure with only a limited amount of disaggregation. The development of a model to determine the performance relative to an individual trip reflecting the network layout must await the development of the discrete vehicle simulations of the AGRT.

In general, new systems have developed measures which relate to the service availability, although not as directly related to passenger trip considerations as desirable. However, in the planning and development stage it may be questioned whether there is a need. The transportation planners do not have a modal split model which can quantitatively assess the input of various levels of service availability. The major use of a service availability index seems to be to measure the service quality of a new system. Evaluation is possible by comparison with current systems. Thus, the major argument would seem to be to develop a measure of service availability for new systems which would relate to the service availability of systems with which transit planners and owners/operators are familiar. In addition, the system developer needs a measure whereby he can derive the reliability requirements of the hardware subsystems and components which he must design and build.

The above reasoning leads to the conclusion that it is necessary to develop an explicit cost model involving the same parameters as the service availability measure. In this manner the cost of providing the various levels of service availability can be estimated. As long as new system performance is "reasonably" close to performance of current "good" systems, it would appear that service availability level is a parameter to be selected by the system planner by means of a cost-effectiveness tradeoff limited by the total project budget.

SUMMARY OF MAIN TOPICS

MORGANTOWN PRT

CONVEYANCE DEPENDABILITY, D:

P_R {SYSTEM READY FOR USE AT RANDOM POINT IN TIME}

X P_R {AVERAGE TRIP SUCCESSFULLY COMPLETED}

$$D = \frac{8760 - DT}{8760} \cdot \text{EXP} \{ - T/MTBF \}$$

DT = DOWNTIME

MTBF = MEAN TIME BETWEEN FAILURES

T = AVERAGE TRIP TIME (5 MIN.)

DUAL MODE DEVELOPMENT

SYSTEM AVAILABILITY, A

$$A = 1 - \frac{VDH}{VOH + VDH} = \frac{VOH}{VOH + VDH}$$

VDH = TOTAL VEHICLE HOURS OF DELAY

VOH = TOTAL VEHICLE HOURS OF NORMAL
OPERATION

SUMMARY OF MAIN TOPICS (CONTINUED)

ADVANCED GRT DEVELOPMENT

SERVICE DEPENDABILITY, SD:

$$P_R \{ L \leq \text{DELAY} \leq U \} = \frac{\text{NO. OF OCCURRENCES/YEAR}}{\text{NO. OF TRIPS/YEAR}}$$

CLASS	<u>LENGTH OF DELAY</u>		<u>FREQUENCY OF DELAY</u>
	L	U	
A	0	3	1 PER 20 TRIPS
B	3 ⁺	24	1 PER 100 TRIPS
C	24 ⁺	45	1 PER 500 TRIPS

OBSERVATIONS

- FOCUS ON EFFECTS OF HARDWARE FAILURES
- MEASURE " DELAYS" RATHER THAN "ON-TIME"
- HIGHLY AGGREGATED MEASURES - AVERAGE TRIP OR NETWORK AVAILABILITY
- NO QUANTITATIVE IMPACT ON MODAL SPLIT MODELS
RELATIVE COMPARISON
- FOR REQUIREMENTS DEFINITION NEED A CORRESPONDING
EXPLICIT COST MODEL FOR COST-EFFECTIVENESS
TRADEOFFS

(End of Paper 1 Presentation)

Mr. Roesler's presentation was followed by a question-and-answer period and by supplementary comments from the floor on Mr. Roesler's concepts. A few of the participants identified themselves, as noted below.

Question 1

Jerry, you talk about disaggregating the service availability measure for large networks, which I think is a good thing. I'm sure you recognize that an operator probably wants to get some kind of an aggregate number out of it. For example, if he has a dozen different numbers to look at, somehow he's going to want to get down to a single aggregate number that will indicate how the system is doing. Isn't that how a Board of Directors would look at it?

Mr. Roesler

Yes, I think that's probably right. But my point of view has always been that you can always generate an aggregate number for somebody. If you start out aggregating the performance measure from the start, then you're sort of helpless if you want to break things down any further. I also believe, in this same vein, that when you do generate aggregate measures, you want to avoid averages, because averages tend to wash out the sensitivity to various changes in the system's design, especially in terms of service quality-type of measures. What's the worst trip dependability your network offers? And how many people does this affect? What percentage of the total trips in your network does it affect? Measures such as this are desirable rather than overall averages. rather than overall averages.

Question 2

Would you please clarify your comments on the AGT model that looks at the travel time, or usual travel time of a single passenger? Does it look at the additional travel time?

Mr. Roesler

It was an attempt to say that if you have a passenger who rides every day, then every two weeks he's going to experience a three-minute delay.

Question 3

I'm looking at these indexes, and the question comes to my mind, what's the use of them? What purpose do they serve? To me, an index of this nature would be some type of management tool which should either ask or answer a specific question or series of questions. And I think the index maker should be guided by the aspect of the problem that affects his work, i.e., equipment reliability, or the viewpoint of the passenger, or how convenient the trip should be to the passenger, or the maintenance point of view. I imagine that each one of these indexes has good points and bad points concerning those particular questions. But in the future, people should look at indexes as tools, not as ends in themselves, but as tools to answer the questions.

Mr. Roesler

I think that's absolutely correct.

Question 4

John Marino from TSC. Just one point on the previous gentleman's comment about usage of an index. I think our entire session here is to talk about this aspect of performance measures, call them what you will, service availability, service dependability, etc. I think there is consensus on the need for a top-level expression of a measure of a system's goodness or poorness in providing service against a requirement that's imposed upon it. Perhaps one thing that Jerry might comment on is the need for terms that can be measured, and that can also be related back to requirements, so that you can indeed match performance against requirement. I think in the AGRT expression you can get **at** vehicle delays pretty easily. Can you talk a little bit about that?

Mr. Roesler

Obviously, being able to measure something is important. However, there needs to be some standardization on how certain quantities should be measured. For example, if you are going to talk about mean time between failures, there needs to be some definition of what you mean by a failure. Is it the actual cessation of travel over a length of network? Or is it the fact that the passenger arrives late or is delayed? Part of the problem with service availability definitions has been that people have been trying to develop something that they think pertains to a passenger. Many different terms have been used, and they generally require different things to be measured.

Let me illustrate this point with a pertinent example. The so-called "on-timeness" is frequently used in conventional transit systems. Certain bus lines have on-time performance in one city of 87%, in another city 67%, in a third city 90%. You may say, "That's fairly close together, not too much different." But then you look at what "on-time" means. In one city it means that they're up to five minutes late for their scheduled time. In another city it may vary from ten minutes before to ten minutes after their scheduled time, and in another city it may vary from two minutes before to two minutes after their scheduled time. Clearly, these measures are not directly comparable, since the criterion for being on time differs so much. And I think the same sort of thing is going to happen in AGT unless there's a lot of definition in the so-called service availability measure.

Question 5

Deane Aboudara, APTA. You talked about service availability, but we have been talking about mean time between failures. Where in your analysis do you put in the other side of the availability coin, which is mean time to repair? We know that mean time between failures is one thing, and we know that as we get more and more complex equipment, it can be out longer for repair.

Where do you take that into account? Because the equipment is out now, mean time between failure gives you one number. But that piece of equipment is going to be out of service for the whole repair period. How do you factor that back into service availability?

Mr. Roesler

Well, there are two things to consider. One, if you look at service availability from the passenger's point of view, what you're looking at is how long it takes to restore service. That's all the passenger cares about. So, if you have a failed vehicle and dump it over the side of the tracks, for example, and get the system rolling again, the passenger may be very happy. However, from the owner-operator's point of view, he has to take that vehicle and get it to a shop and actually spend some time repairing it.

Those factors, as far as I can see, pose a different problem, and are not included in service availability measure; that's why I rather glossed over it and came to the cost effectiveness type of solution. Effectiveness, if you want to think about it, is basically the service availability--how well is the passenger served? The cost aspect is what it is going to cost to provide this service. For example, go back to a rather trivial example, but one which I think brings out the point. In the building of automated vehicles, one approach is to make them highly redundant. It turns out that, from the passenger's point of view, this may be very good, for he sees relatively few failures. However, the fact is that the maintenance shop may be overburdened, because if all the components in a vehicle are effectively made redundant and they have the same high failure rate, the system doesn't fail, but the components are failing at twice the rate that they would have failed with only a single-string type of system. So, the cost of maintenance may go up directly with this redundancy.

Comment 1 (F. C. Smith)

Jerry, could I make a comment on that, please? I think the answer to your question, Deane, is that it's not in the models. That aspect was not in the models; there was some magic mechanism

that is involved in models that Jerry discussed. There's some magic mechanism that restores the system. Now the capability to implement that mechanism by having some magic infinite supply of repaired vehicles is not in these models--it's a separate issue. I'm not saying it shouldn't be in the models, but to my knowledge it's not in the models. That's another issue, and it will have to be reckoned with.

Comment 2

I think what we've got, though, is really two different problems. We have the problem of the operator, who can't spend too much money maintaining the system, and that of the passenger, who rides the system and wants it to be a successful trip. When we try to combine both of those objectives into one measure, we run into problems. We might consider the objectives in terms of separate measures: service dependability for the passenger measure, and operation costs and maintenance costs for the operator measure. This separation could be carried even further on operation costs by distinguishing actual out-on-the-guideway operation from operations in maintenance shops.

(End of discussion on Paper 1)

Dr. MacKinnon

The second speaker is Carl Buhlman. He is Manager of Systems Engineering in the Mass Transit Administration of Maryland. Carl graduated from the City College of New York with a Bachelor's Degree in Electrical Engineering in 1960, received the equivalent of a Master's Degree in Engineering from Johns Hopkins University in 1967, and then a Bachelor of Arts Degree from University of Maryland in 1972. From 1960 to 1973 Carl was Senior Assistant Design Engineer with Western Electric Corporation in the military mockup systems area. From 1973 to the current year he was Manager of Systems Engineering at the MTA State of Maryland, in the Rapid Transit Development Division. Carl's going to provide a discussion of the problems facing the new system planner developing service availability and reliability specifications, in the context of the Baltimore Rail System.

PANEL 1
PAPER 2

SERVICE AVAILABILITY
A DESIGN PARAMETER FOR NEW SYSTEMS

C. O. BUHLMAN

SERVICE AVAILABILITY - A DESIGN PARAMETER FOR NEW SYSTEMS

C. O. BUHLMAN

1. INTRODUCTION

The preliminary design of the Baltimore Region Rapid Transit System has been completed. Standard specifications, definitive plans, and various criteria have been developed and approved. The final design stage is now under way. Contracts have been let to develop conceptual and final designs, and also to develop specifications for equipment procurement and installation.

The basic system will be steel wheel on steel rail, double track throughout. The passenger stations will be center-platform type, 450 feet long, to accommodate a maximum-size train consisting of six 75-foot transit cars. The initial route, known as Option I, a portion of the Northwest Line, will extend from the Charles Center Station to the Reisterstown Plaza Station, a distance of approximately 8-1/2 miles. It will have sections at grade, in tunnels, and also on aerial structures. The transit system will be in operation 20 hours each day, starting at 5:00 A.M. It will run on headways varying from four minutes during peak periods to ten minutes at other times, with future headway as short as two minutes.

The Automatic Train Control (ATC) System will be composed of Automatic Train Protection (ATP), Automatic Train Operation (ATO), and Automatic Train Supervision (ATS).

The ATP will be fully automatic, with provisions for manual operation in the event of a control system malfunction. It will provide train detection, train separation, route security through interlockings, and speed limit enforcement.

The ATO will be partly manual and partly automatic. The train operator will be required to manually open and close the doors and to "start" automatic operation. The ATO will automatically perform train acceleration, deceleration, speed regulation, and program stops. These functions may also be manually accomplished by the train operator.

The ATS will monitor system-wide operation and provide information to a train dispatcher at the Operations Control Center (OCC). This will enable him to direct operations for traffic maintenance

and to minimize delays to the schedule. Initially, the ATS function will be performed manually, with a future expansion capability to fully automatic operation.

It is the intent of the MTA to engage the services of a Reliability, Maintainability, and Systems Safety (RM&S) consultant at this juncture in the program. The Transportation Consulting Division of Booze, Allen & Hamilton, Inc. in Bethesda, Maryland has been selected for the task. This consultant will be responsible for developing, monitoring, and integrating a comprehensive System Assurance Program Plan consisting of reliability, maintainability, and system safety. This work will continue through the final design stage of development of the transit system. It is anticipated that the services in this contract may be extended to encompass the equipment installation and construction stages. In order to achieve the necessary flexibility and continuity through these phases, the consultant will be employed directly by the MTA, and will report to the Director of Engineering and Construction or his designee, Carl O. Buhlman.

2. STATUS AND DIRECTION OF SYSTEM ASSURANCE

The expenditure of public funds imposes a responsibility upon us to ensure that a maximum public benefit is derived from the transit system which is constructed.

UMTA, through its stewardship role to the industry, shares this objective with us; more specifically, that is the attainment of the highest practical level of safety, dependability, and economy. An important step in this direction is the UMTA Safety and System Assurance Program, which will supply technical resources to assist grant recipients in these areas.

It is our understanding that UMTA intends to encourage programs which support management accountability for System Assurance, but still recognize the need for flexibility due to differing local conditions. By funding various R&D programs, UMTA is generating valuable new information which the transit industry alone could not pursue. By conducting numerous seminars

and workshops, such as this, it is evident that UMTA values and solicits the moderating influence of experienced industry management. I have no doubt that this cooperative atmosphere will lead to better and more efficient transportation in the future.

With regard to the key elements of safety, dependability, and economy, there are no absolutes. If we were permitted to spare no expense in these areas, we would soon reach a point of diminishing returns; in fact, an improvement in one area could be detrimental to another. By establishing sound programs, subject to constant review, we hope to develop effective policies and procedures for the successful management of design and procurement up through pre-revenue qualification, and finally, public service.

A comprehensive System Assurance Program Plan would address the major areas of reliability, maintainability, and safety. It is not intended to be a static document; refinements and modifications will be made as the project develops and better data becomes available. Its initial function would be to provide effective goals and criteria for assessment, then to provide early identification and evaluation of potential problems. The program plan is a management tool which not only provides an orderly approach to a complex problem, but it also provides for management visibility, and helps to focus top-level attention on critical areas that may eventually impact operations.

Since the elements of the program plan will occasionally develop an adversary relationship, it is anticipated that the supportive cost-benefit analyses and tradeoff studies will lead to an optimum solution within the real constraints of money and time.

The goal, once again, is to provide safe, efficient public transportation at reasonable cost. We think it can be done.

3. DEVELOPMENT AND USE OF A SERVICE AVAILABILITY PARAMETER

Before discussing service availability, I would like to discuss system availability. As the ultimate operating authority of the Baltimore Region Rapid Transit System, the MTA is highly

cost-sensitive. We plan to employ a definition of system availability which can be related to costs, both initial capital costs and operating costs. This will allow us to set a system availability goal and work toward meeting that goal during the development of the system while minimizing life-cycle cost.

Although we have not finalized our definition of system availability at this time, I would like to propose the following:

- System availability is the degree to which the system will be in an operable condition when called upon.

This definition, when quantified in terms of realistic goals, will allow trade-offs to be made to minimize costs. These trade-offs might involve factors related to maintenance facilities and maintenance equipment, manpower needs and skill levels, equipment reliability and maintainability characteristics. Our system availability goals will be constantly reassessed on the basis of cost. To do this, we are developing a computer program which calculates projected system cost as a function of reliability and maintainability, as well as the capital and operating costs of key system elements. This program is derived from a top-level operations and financial analysis model previously used to calculate the projected capital and operating costs of the Florida Rapid Transit System [Dade County (Miami)]. It will allow us to assess potential cost implications of various levels of equipment reliability and maintainability. We will then be able to assess the sensitivity of key cost elements to selected reliability and maintainability strategies.

The above definition does not directly include service availability (or dependability) in relation to the passenger. Such a measure may be valuable, but we are not certain at this time how such a passenger-oriented measure could be employed in the system development process. What does this mean? Well, consider the following definition:

- Dependability is a measure of system operating condition during periods of revenue service.

How can such a definition be focused to a meaningful application in the system development process? We believe that the daily rider on a system with four- to ten-minute headways cannot be expected to react very negatively to relatively short delays. We, therefore, strongly lean toward a definition of service availability or dependability which focuses on the frequency of long delays rather than toward one which measures schedule adherences, or, in other words, the number of incidents which exceed a specified maximum delay time each year. This approach allows a top-down analysis of various potential delay scenarios, to be undertaken during system development. This is expected to reduce data gathering problems as opposed to an approach which requires a bottom-up analysis of each major piece of equipment.

Ideally, this measure of dependability, given in terms of the probability of the number of long delays per year, should be sensitive to the following factors:

Passenger's waiting time, which is valued more highly than onboard time.

The noncaptive rider, relative to delays in alternate modal choices.

Safety. Platform capacity versus time to safely restore operation, should be a parameter in setting dependability goals.

All incidents relating to weather, accidents, as well as equipment availability.

System demand. Peak-hour situations and long-term unanticipated growth in ridership, such as might occur in another energy crisis.

Our basic philosophy remains that of providing a system that minimizes life-cycle costs by employing off-the-shelf components and proven technology. By the same token, we do not intend to compromise operational safety in order to achieve dependability.

4. SUMMARY AND CONCLUSIONS

The Baltimore approach to service availability will focus on minimizing cost as well as the frequency of excessively long delays. We do not expect to set service availability targets in our specifications. Rather, we will establish, for safety and cost-critical components, such factors as:

- Mean time between failures (by class of failure)
- Mean time to repair
- Mean time to restore.

In all cases the equipment specifications will contain specific reliability and maintainability criteria as well as specific terms for verification and acceptance.

The analytical approach (or methodology) of reliability, maintainability, and safety technologies is already highly developed. The goal for our industry is now to effectively translate this work into the real world as a true system solution. A sub-optimal synthesis of the broader model is likely to provide a more effective balanced solution than the summation of subsystem optimals. Nevertheless, we intend to be pragmatic. We intend to build upon the accumulated wisdom of the transit industry and forgo the temptation of technological risk.

APPENDIX

A DEPENDABILITY MODEL

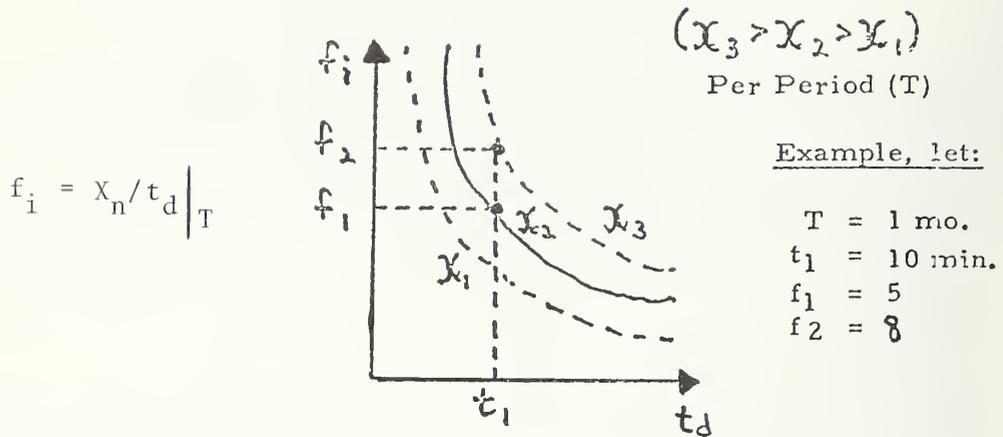
The acceptable level of service availability, from a passenger viewpoint, is called dependability; it appears to be a variable. If one expects to establish realistic criteria to develop subsystem reliability and maintainability goals, he should consider defining this variable. The penalty for using an arbitrary constant could be either an unacceptable level of service or an unnecessarily costly system (or both).

The fundamental premise (yet unproven) is that passenger tolerance for service delays will decrease as the frequency of these delays increases. This tolerance is perhaps based on some cumulative perception of all delays over a recent period of time. This perception period could be two weeks, or a month, or any other interval which reflects the passenger state-of-mind. The passenger state-of-mind can be manipulated to a certain extent, but this is beyond our scope.

Consider delay time (t_d) to a transit passenger as the unanticipated increase in any expected trip time (including walking time, waiting time, and vehicle time), obviously an independent variable. Next consider the frequency f_i at which the average passenger will tolerate a given t_d over a period of cumulative perception T . This becomes the dependent variable. Finally, the passenger tolerance to this cumulative perception will be called X_n . This parameter is a function of the average passenger state-of-mind. It is dependent on perceived factors such as alternate mode availability, comfort, cost, safety, and good-will.

A relationship between these elements can be represented, for T given, by the expression $f_i = X_n/t_d$. Dimensionally, frequency f_i is the number of delay incidents over a specific time interval T , and the units are 1/sec. Since the units of t_d are sec., it follows that $X_n = f_i \cdot t_d$ is dimensionless, as it should be.

Graphically, the relationship appears as follows:



This means that an average transit passenger is constantly re-evaluating the acceptability of his current mode of transportation, and this evaluation is a cumulative process over an average perception period T, perhaps one month. Based on various evaluative factors such as the availability of alternate modes, the perceived safety, cost, comfort, and general good-will, the average passenger is in a certain state-of-mind, say X_2 . Under these conditions, we can say that he will tolerate a certain unanticipated delay t_1 , for example, at a frequency of f_1 . Any greater frequency or time would motivate him to eventually adopt the alternative mode. If the alternative modes deteriorate, or if better public relations cause a relative improvement in his state-of-mind to, say X_3 , the tolerable frequency of the same delay t_1 could increase to f_2 .

This diagram also shows the relationship, or sensitivity, at the boundary conditions. In other words, very short delay times, where t_d approaches zero, can be almost infinitely tolerated. Also, very long delay times are almost equally intolerable (i.e., 45 minutes is not much worse than 25 minutes).

Can it be useful? If nothing else, this exercise helps to understand the nature of these variables, and their relationship. More importantly, it represents a framework, or model, a point

of departure to approach further study and data gathering. No doubt, the model is incomplete; its development and verification (if not rigorously, at least empirically) could lead us to a more cost-effective distribution of reliability and maintainability goals.

(End of Paper 2 Presentation)

The question period following Mr. Buhlman's presentation was opened by Mr. F. Gunter of Westinghouse. Other participants in this exchange of questions and answers included Dr. MacKinnon, Mr. R. Pawlak of Transportation Systems Center, Mr. Aboudara of APTA, and Mr. Sadowsky of the California Public Utilities Commission.

Question 1

Frank Gunter of Westinghouse. How do you plan to handle the situation where individual components do meet the criteria that you specified, and the system doesn't give the service that you need?

Mr. Buhlman

What we're trying to do is balance the approach. We're not going to optimize either one of these elements. We've got cost, reliability, and maintainability to worry about. You can spend a lot of money trying to improve the reliability of something in the design, and find that the thing is not maintainable, that the costs will go up, as we noted earlier on redundancy. Redundancy, by the way, I don't think is a good solution unless you have something to monitor the redundant circuits. One of the redundancies could have failed, and then, when the second one failed, it's just as though you never had the first one. So, I think you can go overboard spending too much money in one direction. Somewhere along the line, what we're going to try to do is start out with some targets, a lot of which are going to be wild guesses. We're going to try a top-down approach; as we go along and develop more information, we're going to flush these things out, and we're going to change a few numbers. From an equipment manufacturer's

standpoint, we don't intend to lay any specifications on equipment manufacturers that can't be verified. For example, if we're going to say that it shall be 85% reliable, we're going to try to specify exactly what we will consider to be acceptable to meet that 85% reliability. In that way we don't wind up arguing over, "Yes you did, no you didn't." And if these things don't work out exactly the way we planned, and they probably won't, that's just part of the job. You've got to make adjustments and see how you can still balance these things against what the other considerations are.

Mr. Gunter

Well, one possible solution which we recommend is to set aside 10% of your money to spend after you get the system operating to fix these things you didn't forecast.

Mr. Buhlman

It will probably be more than 10%.

Dr. MacKinnon

I think an interesting issue has been raised, and that's the issue of accuracy of the analytical techniques. It's very difficult to fully explore the effects of component reliability and availability on service performance index because of the complexity of networks, and because the computation capability of existing computers is limited. So, I think that's probably an issue that should be studied further and highlighted in the proceedings.

Question 2

Bob Pawlak, TSC. Carl, most of the people here are more AGT-oriented than rail rapid transit-oriented. It's my observation that an AGT system, such as the Morgantown system, is put together by a Systems Manager who controls the whole problem. In the case of rail rapid transit you usually have an Authority, like MTA, which does the system-level design with consultants; and then the major components that it buys are construction, vehicle, and train control. It's my observation that you can specify the reliability

and maintainability of vehicle and train control, but the party that has to swallow the specification of service availability is the property, because neither the vehicle manufacturer nor the train control manufacturer supplies maintenance people, diagnostic ability, or failure recovery techniques. These are supplied by the property itself. There's a difference between rail rapid transit and an AGT system where, perhaps, you have one system designer who controls and manages the whole thing, and builds or buys the vehicle, the train control, and the train's central controller. I'm just trying to emphasize the basic difference.

Mr. Buhlman

If I may add to that, we feel at this stage that one of the biggest payoffs in terms of effort expended in the early stages is in the area of designing for maintainability. We're going to give a lot of attention to that because a lot more important benefits can be quite cheaply achieved. At one time somebody's idea of maintainability was a schematic and a screwdriver. And you compare that to a typical Navy approach to maintainability, where you've got simulators and all kinds of training aids, where you take a kid out of high school, and the next thing you know he becomes a first-class technician. I'm not saying we're going to do exactly that, but that's nearly what's required. The existing transit properties are fortunate in having a good qualified staff that grew up with the system. We don't. And we probably won't be able to hire them away from their pension plans and everything else. So, we're going to start with a blank piece of paper, and try to figure out how to organize this thing almost from nothing.

Comment from Mr. Aboudara

I'd like to throw out a suggestion here. You made some laudatory comments about the Navy, and I would second the motion. We have had exceedingly good results from ex-Navy people in this exact context.

Question 3

Mel Sadowsky of California Public Utilities Commission. I was interested in the fact that you have employed consultants to

organize your systems assurance organization. Was this a decision rather than to try to develop your own capability in this particular area?

Mr. Buhlman

Well, the MTA feels that the primary responsibility for safety and system assurance is with the MTA. We will develop an in-house capability to maintain a continuing effort in this area. And the consultant is only considered to be an extra pair of hands on the job. He is not going to be a controlling function. The controlling function will be the MTA. That's the reason for having a consultant report directly to the MTA rather than to a general consultant.

(End of discussion on Paper 2)

Dr. MacKinnon

The next speaker is Donald Gardner, who is a Design Supervisor with the Southern California Rapid Transit District. Mr. Gardner graduated from the University of Southern California with a Bachelor of Science Degree in 1939. His recent experience includes 10 years as an Assistant Director of Engineering with the Technicolor Corporation between 1962 and 1972. He was Chief of Electrical Engineering at Walt Disney Productions between 1966 and 1972. Mr. Gardner is also a member of the APTA subcommittees on automated guideway transit technical problems. He is going to discuss APTA's approach to service availability.

PANEL 1

PAPER 3

APTA'S VIEW OF SERVICE
AVAILABILITY

D. GARDNER

APTA'S VIEW OF SERVICE AVAILABILITY

D. GARDNER

Mr. Gardner

APTA's approach to service availability really reflects the attitude of the operators. APTA's role is that of representative operator, and therefore concerns the problems in keeping a system going and providing a riding public with a service that is transit effective at a cost that can be justified. I think this kind of sums up some of the other remarks that have been made by Jerry and Carl. And so, I hope you'll forgive the redundancy.

Now, when something breaks down in the transit system, the passenger doesn't care who the designer was, or who broke the equipment, or anything else. He knows that he is inconvenienced. So, you might say the operator also represents the riding public, and the riding public votes the money to fund the system. The two factors I mentioned--service and cost--will influence the APTA approach. Let's look at service first.

Simply stated, service availability is a ratio of system vehicles available to those required for use during scheduled operating periods. But service also implies running according to schedule, and this, in turn, demands reliability. One requirement generates still another, and so, on and on to cover all the many other factors that contribute to maintaining system service level.

Looking at cost, we must consider the price tag for that service and the many factors that influence the price tag. The participation of the APTA task force is expected to expedite and facilitate significantly the activities of the project, bringing to bear combined expertise with the transit operating industry. Thus, participation of those transit operators knowledgeable in the transit system design, construction, maintenance, and operation

will provide the benefits of increased efficiency at lower cost. At the same time this will ensure that the end result of the AGT system will be applicable, with due consideration for the wide range of constraints on transit system operation and maintenance in providing service to the public.

The implementation of this program will consist of providing transit industry input and consensus; periodically reviewing UMTA's inputs to the AGTT and the AGRT programs such as this one; providing organization support in planning and conducting workshops; and furnishing qualified personnel to participate in them.

Service availability is but one such topic. Others pertinent to this program include AGT technology, system operations studies, vehicle longitudinal and vertical control, AGT switching, AGT hardware reliability, system and passenger security, and guideway and station technology. In the course of implementation we hope to provide maintenance and operating guidance, and above all, motivation to carry this out. We can talk about it a great deal, but unless we motivate action, not much will occur.

In conclusion, I'm on mobility assignment to APTA on a part-time basis, and I report to Deane Aboudara. I think Deane might want to add a comment to what I've said right at this moment, since he's in charge of the overall program. So, I'll bow to Deane for the moment.

Comment by Mr. Aboudara

Thank you, Donald. The point we're making here is we're really excited, and very pleased, that we've established a legitimate interface with UMTA through a common point, Don Gardner, Program Manager. Don will be feeding in, as the programs develop, a consensus depending upon the subject and topic that the various contractors are being assigned by UMTA in this subject of AGT and AGRT. He will provide a grass-roots, down-to-earth application of existing technologies, separating it from the new futuristic technologies which we must look at, and putting it into the proper perspective of deployment, R&D as opposed to actually operating

systems. We will not repeat the mistake of trying to develop and perfect systems on the production line.

The only message I wish to impart is our satisfaction with the management approach taken by UMTA in providing one input through APTA, among the many others involved in its decision-making functions. We're happy to be here.

Question 1

John Marino, TSC. Donald, or Deane, I was wondering if either or you could comment on whether APTA is putting together a GRT standardized specification with the hope that some of these things could get unified or brought together. Could you comment at all about that?

Mr. Aboudara

Yes, I'm glad you brought that up, John. The AGT task force that was put together in APTA has assembled a user requirements document. We have spent quite a bit of work on that, well over a year, meeting not only with operators but with associate members, consultants, and manufacturers, who are very much interested in this concept. And we have developed a document that pretty well spells out the user requirements. It doesn't get into the details of each of the components such as vehicles, guideways, systems, testing, evaluation, etc. This document is perhaps 95% complete. We have just recently incorporated some observations on system reliability. It's similar to some of the observations we're making here, perceiving the desires of the users. In other words, am I going to be delayed five minutes, two times a year? That document is being, and will be, disseminated. I talked with Duncan MacKinnon about this yesterday. We have the document. When it is disseminated, we hope strongly that it's looked at very hard and read very seriously by those individuals who are going to be involved with contracting efforts. It states very clearly what the users feel is necessary, and what they see. At least, it puts the focus where the focus should be. Now, we are well aware that some of these areas will have to be modified. But at least it gets the

focus where the focus is necessary, and it pretty well sorts out the wheat from the chaff. So, yes, there is a document, it's just about completed. Part of our time here with Don and work with UMTA is to get whatever loose ends are still hanging, complete them, give the document to UMTA, and UMTA will put it into the system and will take whatever action is necessary as we go through the program.

There's another subcommittee requirement in addition to the user requirements, that is, the technical requirements which Bob Pearson back here has done a great deal of work on, which will also be incorporated in this whole program.

Question 2

Art Dickson, STA. It seems to me that perhaps the concept of service availability may hang up on failure recording systems and systems to report delays. I'm wondering, is APTA doing any work along these lines to standardize on reporting systems?

Comment

Jim King, BART. APTA has a committee on reliability, maintainability, and availability. It has three subgroups: a group on definitions, a group on specifications, and a group on reporting. The group on reporting is currently with Frank Chiat of Chicago Transit Authority.

Mr. Aboudara

We have also a contract package that's going through the approval stage with UMTA right now. It's called the Safety and Systems Assurance Package. In that program there is a very significant task identified in the accumulation of data from the properties on their systems availability history.

Jim King mentioned the APTA RAM Committee. We will pull into what we call our task force individuals from these committees, and again, there'll be a program manager, as we have here with Don. That particular effort is going to be about a 2-1/2-man kind of effort because of the many areas we're getting into. But again,

that will start generating this information on a time phase program. You have your committee activities, which you can all appreciate, but you also have to have the output, and this is what these contracts will be doing. They will be starting to actually define and come up with output that can be put into the information dissemination system and used as you start developing policy and implementing design.

In addition to that we also have the ASDP, Advanced Systems Development Project, which contains diagnostic minicomputers. And so it's a topic that's in the forefront today, and is not being overlooked.

Dr. MacKinnon

I'd like to mention a new project that we're starting up, and that's a project with Seattle-Tacoma Airport. They're going to install a data acquisition system in one of the SeaTac vehicles which will accumulate data from about 70 sensors in the vehicle. This data will be used for diagnostic purposes, and also for monitoring.

The next speaker will be Frank C. Smith. He received a Bachelor's Degree in Mechanical Engineering from Yale, and he has also done graduate study at Yale and Southern Methodist University. Currently he's director of a consulting firm, Frank C. Smith and Associates. This firm engages in structural design, consulting, and reliability studies for the Advanced GRT System. Mr. Smith participated in the OTA AGT assessment in 1975, and was also involved in the reliability and maintainability analyses for the Twin Cities Metropolitan Transit Commission's small-vehicles study.

PANEL 1

PAPER 4

ANALYSIS OF SYSTEM DESIGN
WITH RESPECT TO SYSTEM COST

F.C. SMITH

ANALYSIS OF SYSTEM DESIGN
WITH RESPECT TO SYSTEM COST

F.C. SMITH

I will deal with the methodology which relates system cost to its reliability and maintainability, and lists information that should be obtained to assist in the design of economically viable systems. The analysis also shows where money should be spent - in the acquisition phase or in the subsequent operations and maintenance phase. The life-cycle cost of a transportation system may be defined as the sum of three elements:

- a. The acquisition cost, which includes the design, development, and installation cost of the system, including debt service and related nonrecurring costs. Note that the acquisition cost of modern automated systems is large compared to other costs over the service life of the system; in fact, the analyses presented below indicate that it is the predominant cost. This fact is both good and bad.
- b. The maintenance cost, over the service life of the system, which consists of the scheduled maintenance cost (cleaning, washing, and other preplanned costs), and unscheduled maintenance costs resulting from failures. (Vandalism and accidents are not considered in this analysis.)
- c. The operational cost, which consists of the wages, salaries, and other expendable costs to operate the system.

The acquisition cost (AC) of a typical transportation system can be expressed by Equation (1):

$$AC = WC + N (VC) \quad (1)$$

WC = cost of wayside system

N = number of vehicles in the fleet

VC = unit vehicle cost

The maintenance cost (MC) can be expressed by Equation (2):

$$MC = M_W + NM_V + (SM) \quad (2)$$

M_W = cost of unscheduled wayside maintenance

M_V = cost of unscheduled vehicle maintenance/vehicle

(SM) = cost of scheduled maintenance - constant

The operational cost will be assumed constant for each year of service life.

A key point in the economic analysis is that some of the acquisition reliability and maintenance cost elements can be affected by the system design in that efforts to improve reliability and maintainability of such elements affect system cost, whereas reliability or maintainability improvements in other system elements have little effect on system cost. For example, one of the major costs of a new guided transit system, as shown in table 1, is the construction and installation of the structural portion of the guideway and associated stations. However, if these elements are designed and constructed in accordance with conventional civil codes and practices, their lifetimes are essentially infinite, and it appears that little or no effort should be made to improve their reliability and maintainability. (The one exception may be the need to improve rail-bed design to reduce track maintenance costs.) On the other hand, some of the mechanisms, such as door operators, train command and control systems, and train propulsion systems have rather large failure rates, and their reliability and maintainability can be affected by introduction of money into the acquisition phase of such subsystems.

TABLE 1. ACQUISITION COST OF AN AUTOMATIC GUIDED RAPID TRANSIT SYSTEM SHOWING COSTS AFFECTED BY RELIABILITY/MAINTAINABILITY

ELEMENT	SYSTEM "A"		SYSTEM "B"	
	NOT AFFECTED	CAN BE AFFECTED	NOT AFFECTED	CAN BE AFFECTED
Guideway Structure	\$33.0 m	\$ -	\$435.2 m	\$ -
Switch System	-	2.0	-	-
Stations	5.5	.5	90.8	9.0
Vehicles	3.0	6.0	12.0	28.0
Wayside Control System	-	8.0	-	25.0
Electrification	3.0	4.0	60.0	33.7
Communications	2.0	4.0	2.0	5.0
Other	-	-	141.0	12.0
Total Estimated Cost	\$46.5 m	\$24.5 m	\$741.0 m	\$112.7 m
	\$71.0 million		\$853.7 million	

Proposed	Initial
Small PRT	Denver PRT
System	System Cost
Cost Est.	Est.

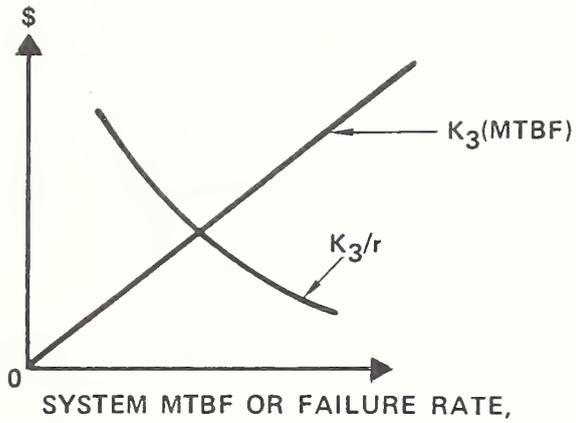
Excludes debt service \$

During the acquisition cost phase of the project, it is desirable to improve system reliability and maintainability by design and development testing. Generally speaking, such effort will increase the acquisition cost, and it is assumed that the acquisition cost is directly proportional to system MTBF, as shown in Figure 1(a). Figure 1(a) also shows a qualitative plot of the effect of system failure rate on acquisition cost, and shows that as the failure rate increases, the development costs go down. Likewise, proper design can decrease the Mean Time To Restore (MTTR) the system; for example, the use of modular components will decrease the time to restore, but will probably result in higher acquisition costs. Figure 1(b) shows these trends, and assumes that the acquisition cost spent on improving maintainability is inversely proportional to the MTTR, such that poor maintainability (large MTTR) results in lower system acquisition cost.

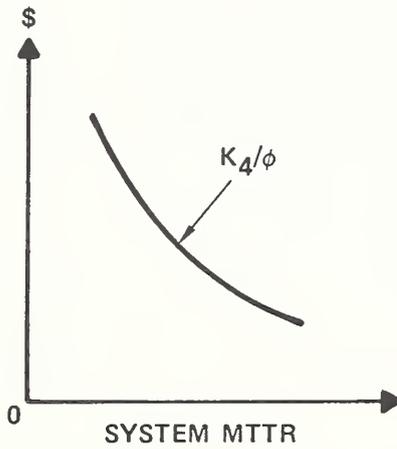
Variations in life-cycle and system assurance costs with respect to the frequency of system failures and restoration time requirements are shown in Figures 2 and 3. The figures also include optimum conditions which result in minimum costs.

Several conclusions can be deduced from the facts presented here and from data obtained in the continuing survey of the system cost and reliability/maintainability relationship:

1. For capital intensive guided transit systems, the overwhelming portion of the Life Cycle Cost (LCC) is produced by costs which have little or nothing to do with system maintainability or reliability.
2. Significant improvements in both system reliability and maintainability can probably be obtained for investments of less than 2 to 5% of the projected LCC applied during the system acquisition phase.
3. However, optimum values of both MTTR and MTBF exist which minimize LCC, and designing optimum systems should reduce maintenance costs substantially and improve schedule reliability and, hence, customer acceptance.



(a) RELATIONSHIP BETWEEN ACQUISITION COST AND SYSTEM FAILURE RATE (r) OR MTBF



(b) RELATIONSHIP BETWEEN ACQUISITION COST AND SYSTEM MEAN TIME TO RESTORE (MTTR)

FIGURE 1. QUALITATIVE ACQUISITION COST TRENDS

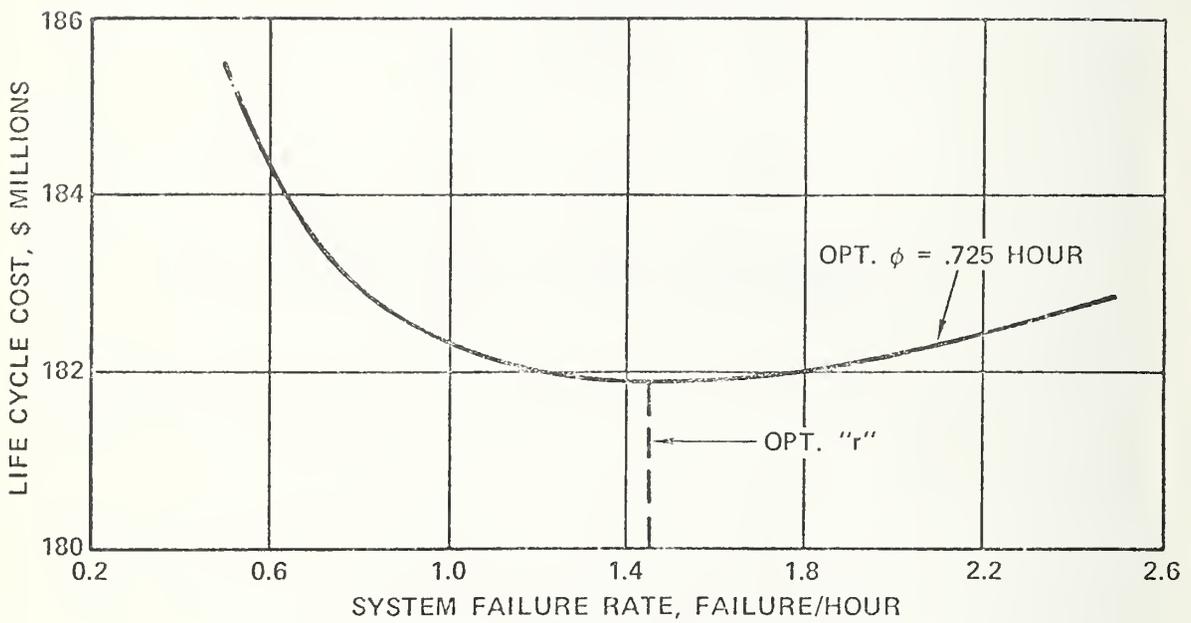


FIGURE 2. EFFECT OF SYSTEM FAILURE RATE (r) AND MTTR (ϕ) ON LIFE CYCLE COST (SYSTEM "A" - INCLUDES DEBT SERVICE, 20 YEARS AT 6 PERCENT)

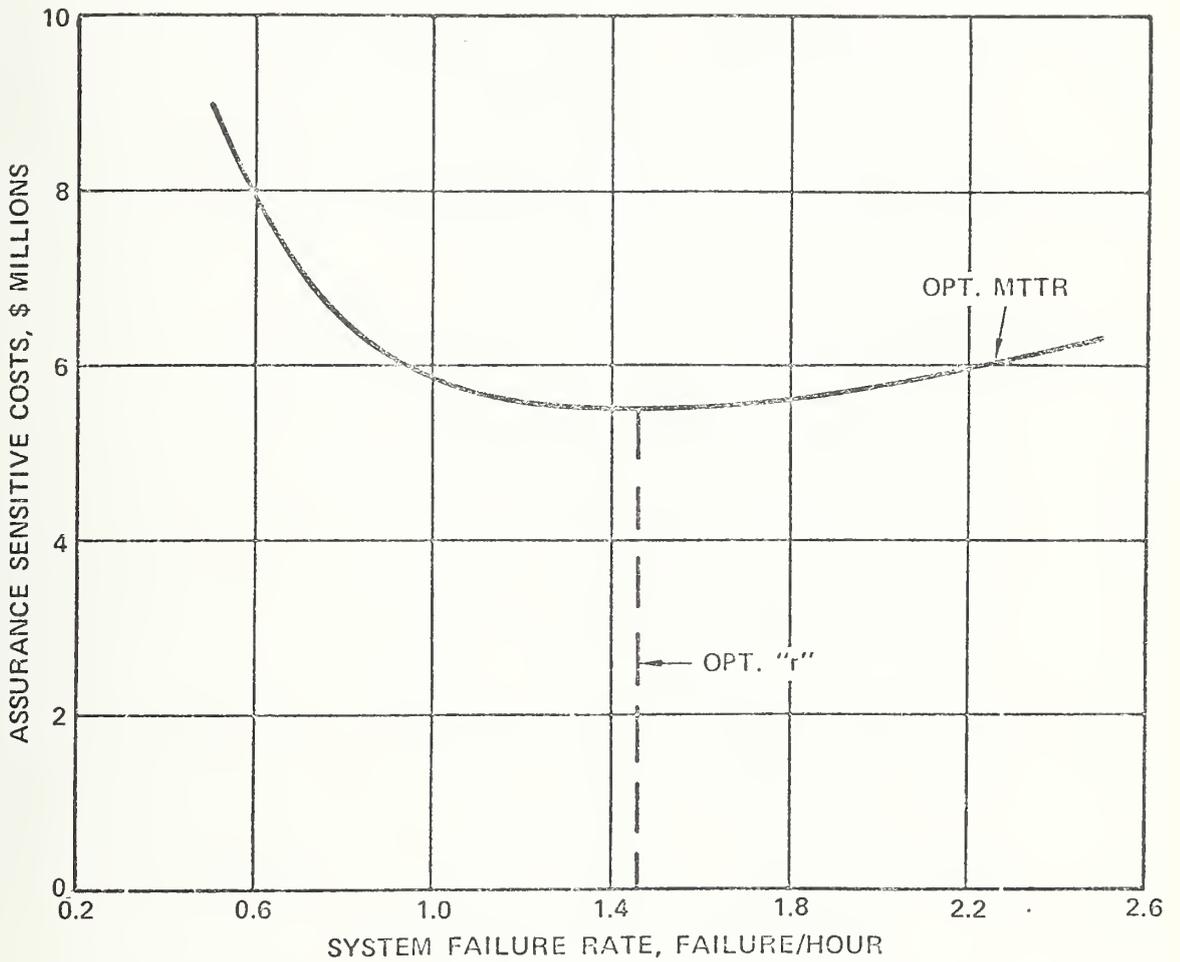


FIGURE 3. EFFECT OF SYSTEM FAILURE RATE ON COSTS SENSITIVE TO SYSTEM ASSURANCE (SYSTEM "A")
 (End of Paper 4 Presentation)

Dr. MacKinnon

Thank you very much, Frank. The panel is now open for questions.

Question 1

Frank Gunter, Westinghouse. You pose a very interesting proposition. It boils down, in effect, to specifying a particular design of component. I think we would be interested, and I assume other manufacturers would be interested, in entering into reliability improvement programs for components if we could get those components specified as acceptable items.

Now, New York City Transit Authority has done this for years by actually specifying the use of certain contactors, by type number in their specification. I wondered if it would be possible, under the kind of financial and contract constraints that Baltimore has now, of entering into a contract with Westinghouse and GE and Garrett, say, for instance, to design a better gear box. In effect, would it be possible to qualify a better gear box or a better motor in each of the three designs, and then have each of those specified in the vehicle contract?

Mr. Smith

What I'm really saying, and of course Carl can answer the question, I think it would be great for the industry as a whole if at least Baltimore would ask you to give it a serious estimate on such a program. That's all I'm interested in, as an opener.

Mr. Gunter

Well, the problem with that is, you don't have any hard results. The estimate might not result in the hardware improvement we're talking about. You might spend the money and not get it.

Mr. Smith

That might be true if, for instance, you sit down, order a couple of drinks, and state casually that the improvement might cost about two million dollars. What I'm saying is that you can do better than that.

Mr. Vigrass (PATCO)

My colleagues are at this very moment negotiating price for 46 new transit cars with Canadian Vickers, using plans similar to those for the original cars. And we have specified some very specific components. We have been dismayed at the monopolistic prices that have resulted from this approach. Certain suppliers quoted prices two to three times what the engineers thought was appropriate. So now we have to seek as alternatives components we don't really want, simply for reason of price. There is, indeed, a real problem specifying specific hardware. As you say, New York either has multiple sources of specific hardware, or somehow they don't mind prices.

Mr. Gunter

What it really boils down to is that they are specifying a GE item, or a Westinghouse item, or an item of some other supplier. But, in order to accomplish that, say in a Baltimore type situation, you really have to go through some sort of preliminary qualifications of the program, including testing of hardware.

Mr. Buhlman

The two-step procurement process is one of the things we're considering in some of these areas, in which the manufacturers will be allowed to compete. It hasn't been established yet exactly what the areas will be, but I hope that reliability and maintainability will be among them.

Mr. Musil (Boeing)

You're talking about considering a system. Previously, some of the data had to do with availability of transit systems. I assume you're looking at maybe a train, or a car, or more of a component. Your approach is optimizing, or attempting to optimize, on a lower level.

Mr. Smith

This is an entire system - 40 cars and 25 miles of guideway, and switches and whatever.

Mr. Musil

Well, then the problem here is that, with the existing criteria for defining success or failure, and with those systems which are made up of complicated pieces of equipment in various modes of degradation, your whole system may be in a gray area; i.e., it does not operate successfully, yet it does not fail. How would you address that type of a problem?

Mr. Smith

My feeling is that it is desirable to have available some reasonable model of the system. I don't think any of us could accept without question the curves you see about an area as complex as this. I think people are still contesting the meaning of a stress vs strain curve, and that's a pretty simple model. But I also believe that any effort at system rationalization, e.g., a reasonable model, is better than no effort at all.

Mr. Gunter

I think our mutual purpose here is to avail ourselves of everybody's experience, and thereby to obtain as realistic a model as possible with which to arrive at reasonable examples of system operation. We also wish to talk about mean time to repair and mean time to restore. In many of the systems, the downtime is not the actual restoration time. Most of the downtime is non-restoration time. So, when you try to optimize these types of models, you have to really consider some other very important factors.

Dr. MacKinnon

Mr Smith will accept one more question or comment.

Dr. Doyon*

I want to say to you, Mr. Smith, I enjoyed your remarks very much. It brings back memories of my own years in the

*Leonard R. Doyon, Ph.D., Assurance Technology Corporation, Carlisle, Massachusetts

aerospace industry, back about 15 or 20 years ago, when we had quite a bit of difficulty convincing our own management and our own engineers that we ought to put clauses in reliability, penalty clauses as well as incentive clauses in our contracts. As for the fear that we would have no one to bid and that the cost would skyrocket, we found, and we support what you say, that the costs when the bids came in did not reflect this great increase in cost. And I'd like to add to what you said about the myth that if you put a stringent reliability clause in a contract, you'll have nobody bidding on it. In our case, that also was a myth. We found that good companies are in business to take risks, and are willing to do it as long as they have incentives, as long as it's worthwhile. So, the only objection we found, in the long run, was the inclusion of penalty clauses in contracts if there were no incentive clauses for them to make it worthwhile. So, I support wholeheartedly what you say.

(End of discussion on Paper 4)

Dr. MacKinnon

I think we'd better close questions at this time, because we're getting behind schedule. Our next speaker is Mr. Lee Tucker, who's the Program Manager in our branch at UMTA. He graduated in 1961 with a Bachelor of Science Degree in Physics from Adelphi University, and obtained his MS Degree in Physics in 1965 at New York University. He has done extensive work for his Ph.D. Degree at the University of Buffalo and at Johns Hopkins University. In July 1976 Lee joined UMTA, where he's helping me to manage the System Operations Studies program and the urban deployability aspects of the Advanced GRT program. Prior to joining UMTA he was with the Calspan Corporation between 1970 and 1976. While there, he was involved in the management of high-performance PRT. He also directed transportation systems research programs, including the FHWA Automated Highway Practicality Study. Prior to joining Calspan he was with the Grumman Aerospace Corporation, where he was involved in extensive analysis of control systems and hybrid simulations on the Apollo. Lee:

PANEL 1

PAPER 5

ANALYSIS OF SERVICE AVAILABILITY
RELATIVE TO ADVANCED GRT PROGRAM

H.L. TUCKER

ANALYSIS OF SERVICE AVAILABILITY RELATIVE TO ADVANCED GRT PROGRAM

H.L. TUCKER

What I'm going to discuss are the studies associated with service availability that were involved with the Advanced GRT program, which is now in Phase 2a, as most of you know. The problems that we've observed in systems prior to Advanced GRT or HPPRT, like in Morgantown, the AIRTRANS, certainly point to the need to guarantee, while the system's in preliminary design, and before detail design and prototype development, that you can achieve at least minimum requirements for service availability. So, in addressing this problem on the Advanced GRT program, we have certain tasks that each one of the three contractors is performing in order to ensure that those systems will be designed to meet those goals, such as were discussed by Jerry Roesler this morning.

First, we want to define what reliability requirements are necessary in order to meet the availability goals. And, as you might guess, in certain cases you're going to have to make changes in the equipment and the base line configurations to meet those goals. Associated with that objective is the impact of reliability and availability on system design.

Finally, after we have the base line system, there's a task directed toward the objective of determining what the impact of this is on the systems operation, and then, of course, the costs. So, if we can meet all of these objectives, and it is certainly our intention for the contractors to do so, then we'll have a successful program.

Now, there are three basic tasks in this area. One task is to derive the plan for actually performing the availability study. That plan subtask I'll expand on shortly. The second task involves the availability and reliability study itself, which will naturally include some simulation. Finally, we have a larger scale problem demonstrating that the concepts and effect on performance and operations will operate for our system. That's the third task.

The first task of the reliability plan requires defining exactly which studies are conducted, the formats to be used, and the simulation studies to be performed in order to meet the objectives. It is further required to develop failure management algorithms on how to remove the failures and how to respond to a build-up in passenger queues or vehicle queues as the systems come down and have to be restarted. Then it is also necessary to determine what the interrelationship is of the availability, reliability, and safety. So, with that plan we move into the next sequence, which is the actual performance of the study.

Now we turn to the subsets and first provide the definition of the base line system. This base line system does not usually include redundancies that you might expect. Redundancies are based on the preliminary analysis, and then are iterated as you come to determine what the design changes need to be. But first, define the elemental system, and then go through a failure modes and effects analysis; look at where the critical failures are, the single point failures and high failure rate items, and then apply all the information to a data base, and actually go through a determination of what the dependability of that configuration is. With that information in hand, iterate on the design to try to prove that performance. Go through and essentially redo the operation; look at the system sensitivity, which areas it pays to concentrate on, which are the ones that have the highest payoff in terms of improvement, and then pick out those criteria and options and perform tradeoffs. Again reiterate the design and evaluate the dependability safety of the final basic.

Now, there are several techniques as well as some analytic concepts that are going to be discussed tomorrow for addressing the dependability or availability results. One of the tasks involves a very detailed, very precise Monte Carlo simulation of a network subelement, the one I was referring to in Frank Smith's approach. In that particular simulation it models the restoration probability densities and pulls out the random numbers for the different classes of failures and classes of delay times.

Another interesting thing about this rather detailed subelement simulation is that it accounts for compressibility of flow. By compressibility of flow we mean that if you have a vehicle that stops in the guideway, and if the delay or period of stopping is short, then it may not be necessary to bring everything tracking down behind it to a full stop. That is accounted for in the simulation, so that vehicles further downstream may not even be affected by the failure.

Finally, this particular Monte Carlo simulation looks at a subnetwork. We need to know what the effect is in the entire network system, and doing a detailed Monte Carlo simulation may be prohibitive. Therefore, the approach that we are taking with the contractors is to look at the failure management performance on a rather deterministic nature for a specific network, with the contractors picking the points in the network in terms of failure times to study. So, it provides at least a snapshot of failure management performance at those times.

Let me indicate some of the types of conditions that we've recommended to use for that type of analysis. First of all, when you look for classes of failure modes, you can find that a lot of them can be grouped, and certainly many of the critical ones can be grouped in the guideway link blockage case. We've taken that as the most critical item, and we're applying these particular failure modes to what we call Network 2 as far as it is used by contractors. This network has two-way links coming in from the radial, and a one-way link in the CBD area, as well as two-way crossovers. Now, as far as the failure management approach is concerned, it's expected that each one of the contractors will consider guideway geometry modifications to ease some of the congestion that may occur due to a failure. That approach is based on their individual judgments. The demand profile that is associated with this network follows a profile that builds up in the morning, especially in the CBD, goes down to a mid-day level, builds back up as people go out during the afternoon rush hour, and then drops off to a low nighttime level.

Again, failure times, the duration of the failures, are being established by each one of the three contractors. The location of each failure within this network is also being established by the contractors. Based on their particular design, they're picking the points where these failures have the greatest effect. That's the approach that we've taken. We think that there is a lot of additional work that could be done. However, by doing at least these tasks, we'll have enough confidence in the availability of the system, so that when we go on Phase 2b, we'll at least have some assurance that we can handle most of the reliability-availability questions. That's the extent of my comments.

(End of Paper 5 Presentation)

Mr. Marino

Jerry this morning indicated that we have to date exposed differing expressions that have been used on Morgantown, Advanced GRT, and AIRTRANS. Westinghouse has used either one, or more than one. On the Advanced GRT, have you done any further analysis? Can we say at this point that we plugged in some of the information of, say, Morgantown to see whether or not our goal is more stringent or less stringent? How does it compare in terms of dependability with the ones that have been operated on? Are we shooting for a higher mark, or are we shooting at the same low mark?

Mr. Tucker

Let me try to answer that. I don't know specifically that that analysis has been done. I know from Phase 1 work, based on estimates of, say, the Morgantown system with enhanced design, what the effect of the enhanced performance would be on availability. So, picking availability goals of 0.96 to 0.98, something of that order of magnitude, a set of MTBFs and MTTRs was derived, at least in the Phase 1 design, that indicated it was feasible to talk about levels like that. Phase 1 did not do all the detailed analysis that we intend to do in Phase 2a. But I think enough was done to at least provide some indication that we can achieve availability of these types of systems.

Mr. Marino

I wonder if Boeing has perceived the Advanced GRT requirement to be more stringent.

Mr. Tucker

I think they perceive it to be more stringent, but I would rather defer that question to a representative of Boeing.

Mr. Robert Tidball (Boeing)

Yes, it's more stringent. For example, there are limits on maximum delay and total delay.

Comment from Audience

In this model we must consider the effect of delays on the system. We almost must consider the effects of congestion on a link rerouting around a failed link. Those all add to the time as perceived by the passenger. So, it's not just the system availability, and it is not just failures; it's the way your control system operates as well.

Mr. Tucker

I agree with that. Again, we've got to discuss that in the issue of availability. I think we all agree that it has to be in terms that can be related to what the passenger experiences. Just talking about what the equipment is doing is of little relevance.

(End of discussion on Paper 5)

Dr. MacKinnon

Our next speaker is David Heimann, who is a mathematician at the Transportation Systems Center. Dr. Heimann graduated with a Bachelor of Science Degree in Mathematics in 1968 from City College in New York. He received an MS Degree in Mathematics from Purdue in 1970, and a Ph.D. Degree in Computer Science from Purdue in 1974. Since 1974 he has been a mathematician at Transportation Systems Center, where he has addressed problems of reliability, maintainability and availability modeling, and application of some of these modeling

techniques to the MBTA System. He has also done analysis on the airport landside capacity problem. Dave is going to discuss service availability as related to the AGT system reliability and service availability program, the systems operations studies program, and some of the other research he's been doing. Dave:

Dr. Heimann

Thank you, Duncan. I'm going to talk about TSC participation in the field of availability involving the AGT program, service availability and system operations studies, and the safety and systems assurance program.

PANEL 1
PAPER 6

AN AVAILABILITY ANALYSIS OF A
RAIL RAPID TRANSIT SYSTEM

D. I. HEIMANN

AN AVAILABILITY ANALYSIS OF A RAIL RAPID TRANSIT SYSTEM

D. I. HEIMANN

1. INTRODUCTION

The formulation of various measures of availability for system specification, description and design has been recently studied. The application of this availability technology to existing systems is, however, rather limited.

This paper is a preliminary report on a demonstration of the use of the concept of availability to analyze the operations of an existing line-haul rail rapid transit system. The example being examined for the purpose is the Red Line of the Massachusetts Bay Transportation Authority (MBTA).

The eventual objective of this effort to use the availability concepts, described in Heimann, (Reference 1 in Section 10.0) is to develop guidelines for the formation of good system level specifications which meaningfully describe the resistance of a (line-haul) transit system to failures and other similar incidents. Such guidelines will also develop the connection of these specifications to operating and maintenance policies and subsystem specifications for reliability and maintainability. These will, in turn, result in better design of new systems and better operation of existing ones.

After presenting a physical description of the Red Line and also a brief discussion of the availability concept, this paper examines what kinds of operational data are kept by the MBTA and how the existence and form of this data affect the choice of a proper availability measure to describe the system. Ideally, one would choose that measure that most accurately reflects system performance; however, the data requirements for a specific measure often preclude such a choice. For this exercise, existing data directly influenced the choice of the measure(s). In future availability analysis, the kinds of data collected will remain the constraint upon the choice of the measure. The kinds of failures (incidents) which occur on the MBTA, their effect on operations, and various actions the MBTA carried out in response to these incidents were studied. To illustrate these interactions, a set of sample incidents, responses and their effects on the system are presented.

2. AVAILABILITY - AN OVERVIEW

The concept of availability (or dependability, as it is often called) is being looked at with increasing interest by those concerned with transit systems. Availability is a measure of how strongly failures and other similar incidents impinge on the performance of a transit system, and thereby cause it to deviate from its nominal performance level. As such, availability measures how often the system delivers satisfactory service to its users where "satisfactory

service" is defined in terms of the nominal performance level.

Availability is one of several parameters which go into describing the "effectiveness" of a system. Other such parameters include the cost of building and operating a system, and the nominal performance level itself ("level of service"). Very often in the recent past not enough attention was paid to availability during the planning of new or revised systems, due to the complex interrelationships among the overall system makeup, the subsystems, the operational policies, the technical specifications used, etc., which must be taken into consideration in a proper availability analysis. As a result, while the resulting systems performed reasonably well under nominal conditions, they proved unexpectedly vulnerable to failures. The situation caused many in the transit field to realize that more attention had to be devoted to availability and its analysis.

An availability analysis is an organized way of assessing a system from the point of view of minimizing the frequency of incidents and their impact on the system. An incident is any event which adversely affects the operation of a system. Failures are the most common type of incidents that can be controlled by equipment design and maintenance procedures. There are other common incident-related factors that are almost impossible to control, such as operators who start their trips late or operate slower than scheduled, suicide attempts within the station area, or excessive dwell

time because of passenger disturbances. The principles used in the analysis are not complex; they are mostly the usual design concepts, well known to design engineers and operators, such as reliability, maintainability, determination of operating policies, etc. The merit of an availability analysis is that the analysis shows how they fit together to explain the system interrelationships, and how they are used to develop an incident-resistant system.

In (1), the conceptual framework of availability was developed. Particular attention was devoted to the question of quantitatively defining the availability of a system. Criteria for a good definition were presented, followed by a list of candidate definitions along with the data requirements for each one. These definitions were of various degrees of sophistication, the more sophisticated ones describing more accurately the availability of the system from the user's point of view, but requiring more data than the simpler definitions. The various definitions were compared, and an example was presented to demonstrate the calculation of availability from reliability, maintainability (recovery from failure), passenger demand, and operational information.

This paper is, in essence, a progress report of an effort to test the applicability and utility of this conceptual framework on an example transit system, the MBTA. This effort is important in the development of availability as a strong tool for transit system analysis, for several reasons:

1. In order for the availability concept to be useful, it must be applicable to actual (or actually-planned) systems.
2. A good availability measure must be calculable with data that can be feasibly obtained. Using an actual system provides a guideline as to what kinds of data these are.
3. Using an actual system provides a better picture of failure modes and effects, operating procedures, failure management, scheduling, etc.
4. The results can be of immediate use.
5. Many systems are similar, so work on one can be applied to others.

3. DESCRIPTION OF THE MBTA RED LINE

The Red Line is one of four rail rapid transit lines operated by the MBTA. The Red Line's northern terminal is at Harvard Square in Cambridge. From there it travels eastward through Cambridge, and then crosses the Charles River, entering the central business district (CBD). Beyond the CBD at Andrew Square, in South Boston, the Red Line splits into two branches. The older branch continues through the Dorchester area of Boston, with its southern terminal at Ashmont, while the newer branch (opened in 1971) runs express for several miles to the neighboring city of Quincy, where it makes three stops and terminates at Quincy Center.

About half the vehicles used on the Red Line are among the newest ones of the MBTA rail lines. The signaling system operates with the usual wayside signals and trip stops, except on the Quincy branch (south of Andrew Square), where in-cab signaling is used.

4. A SURVEY OF THE MBTA DATA RECORDS

The data pertinent to availability kept by the MBTA fall roughly in the following categories:

1. Scheduled and actual arrival times at various points along the route
2. Incidents which cause delays
3. Maintenance records
4. Vehicles required on route vs. vehicles available for use
5. Passenger demand.

4.1 Arrival Time

Scheduled and actual arrival information is kept for each run over the course of a day by the dispatchers. For each run, the following is recorded:

1. Car numbers for each car of the train (and by implication, the number of cars in the train)
2. Time leaving Harvard southbound
3. Time arriving at Andrew southbound
4. Time leaving Quincy northbound
5. Time this train is next due to leave Harvard southbound
6. Cuts (4-car to 2-car train), adds (2-car to 4-car), and removals (taking train off the line)
7. Remarks, in case of delay or non-routing action.

For items 2-4, there are two times listed for each; the scheduled time, preprinted on the form, and the actual time, handwritten by the dispatcher. The actual time leaving Harvard is always shown, while the other actual times are indicated only if they are significantly different from the scheduled time.

4.2 Incident Record

A form is maintained by the dispatchers for all delay-causing incidents on the MBTA Red Line. The blank form is kept on a typewriter in the dispatch room, and as an incident occurs, the dispatchers type in the proper information as soon as they're able, while events are still fresh in their minds. The facts indicated on the form are:

1. Location of the incident

2. Time of day
3. Description of the incident
 - a. How was incident noticed?
 - b. How was incident diagnosed?
 - c. Diagnosis of the incident
 - d. Action taken
 - e. Effect of incident (in a general way -- not detailed delay information)
4. Person reporting incident.

A spot check, matching the incident and arrival time forms for a given day, was carried out. For the most part, the two forms were consistent, showing an incident on the incident form at the proper time to explain a discrepancy on the arrival time form, and vice versa. This is good, as it allows one to calculate the effect, in terms of delay time, for each incident.

4.3 Maintenance Records

Two arrangements of records are kept on maintenance for the assessment of system performance, one arranged by specific car, and one arranged by specific day. In each are entered either the day or the car number, as appropriate, the fault, the repair made, the repairman who did the work, etc. It is therefore possible, though not a routine matter on a large scale, to use the incident log and repair records to link an incident to the cause found for it and the repair carried out.

There are plans underway to computerize these records. If carried out successfully, computerization would allow large-scale cross referencing of incidents and causes, which could lead to finding patterns (such as strong correlation between two apparently unrelated types of incidents) which otherwise would be unnoticed.

4.4 Vehicle Demand

A form is maintained for each day, during both the morning and afternoon peaks, indicating the number of cars available, and the surplus or deficit. In addition, the number of cars disabled during the peak hours (and the number required to unload their passengers) and the location of the spare cars (if any) are recorded.

This form is useful to determine how often vehicle shortages occur, and how severe they are when they do occur. It also functions as a "pointer" in a similar way as does the incident form, to explain delays shown in the arrival time form. (It explains any delay due to a shortage of vehicles.)

4.5 Passenger Use Data

Sufficient data useful for determining passenger loading of vehicles is not presently compiled. There is information of the number of passengers entering the system during the day at each of the various stations.

Additionally, for schedule planning purposes, measures are taken from time to time for the maximum peak hour passenger load of a car at each of the points where the line enters the CBD (Charles St. and South Station). However, this is not enough data to give more than a very rough estimate of the passenger loading at a particular place and time.

5. COMPARISON OF AVAILABILITY MEASURES

In (1), various alternative measures of availability, of varying degrees of sophistication and data requirements were presented. It was mentioned there that the choice of a particular measure for a given application depends on the data available. The usefulness of each of the various measures in the light of the data kept by the MBTA was assessed.

The most significant fact about the MBTA data is that the vehicle delay is much more detailed than the passenger loading (demand) data. Using the arrival time charts, it is possible to determine the delay incurred by each train run during the day. On the other hand, because of the lack of detail of the demand data, together with the fact that the arrival time chart shows schedule discrepancies only at terminal stations (and Andrew Square southbound), not at all

stations, it is impossible to determine the delay incurred by each passenger. Detailed calculations of vehicle-based availability but only very rough estimates of the passenger-based measures can be made. Therefore, of the eleven measures discussed in (1), three can be readily calculated:

a. Vehicle-based Proportion of Delay:

$$A = \frac{\text{Uptime}}{\text{Uptime} + \text{Downtime}} \quad (\text{Time is vehicle hours})$$

b. Vehicle-based Successful Trip Ratio:

$$A = \frac{(\text{Total trains run}) \text{ minus } (\text{Trains delayed more than } d \text{ minutes})}{\text{Total trains run}}$$

c. Relative Vehicle-Based Successful Trip Ratio:

$$A = \frac{(\text{Total trains run}) \text{ minus } (\text{trains delayed more than } d\% \text{ of scheduled trip time})}{\text{Total trains run}}$$

Of these, for reasons discussed in (1), the successful trip ratios (b) and (c) more closely describe system availability for the user's point of view, and so are preferable to (a). Since the intended trip time of all trains run on the Red Line are similar, there is no actual difference between (b) and (c).

In addition, two of the passenger based measures can be roughly estimated:

d. Proportion of Delay:

$$A = \frac{\text{Uptime}}{\text{Uptime} + \text{Downtime}} \quad (\text{Time is in pass. hours})$$

e. Successful Trip Ratio:

$$A = \frac{\text{Number of passengers not delayed more than } d \text{ minutes}}{\text{Uptime} / (\text{Uptime} + \text{Downtime})} \quad (\text{Time is in pass. hours})$$

6. CLASSIFICATION OF INCIDENTS

The delay-causing incidents which affect a line-haul system such as the MBTA can be broken down, for the purpose of determining their effects on the system, into various categories. These categories are: vehicle halt, vehicle halt and passengers off-loaded, vehicle slowdown, slow point on wayside, deleted scheduled run, and catastrophic delay (plus, of course, combinations of these). This section describes these various categories and the effects each has on system performance. The next section presents some illustrative examples.

6.1 Vehicle Halt

A vehicle halt occurs when a vehicle comes to a complete stop on the system, other than because of a normal station stop or layover at a terminal. This can be caused by a malfunction in the vehicle such as the propulsion system, braking system, doors, or car-borne signal devices; a malfunction in a wayside device such as a signal or switch; or by a late departure from a terminal, for reason other than a malfunction.

The effects of a vehicle halt are:

1. The affected train is delayed initially for a certain length of time.
2. Trains which follow the affected one may also be delayed. If the delay to the affected train is d , and the difference between the normal headway and the minimum safe headway is h , the second train will be delayed by $d-h$, the third by $d-2h$, and so on.
3. Passengers waiting at stations downstream of the delay point will be delayed by the same amount of time as the affected train. However, at the end of the delay there will be a momentary increase in system capacity, as all the following trains which have been delayed will arrive at the downstream stations as soon after the affected train as safety will allow. Therefore, if one train following the affected one is delayed, the capacity will be momentarily doubled; if two are delayed, it will be tripled, etc. (This assumes that the minimum safe headway h is smaller than the normal headway by at least a factor of four, as in the example of Section 7.0).
4. There will be additional delays to the affected train (and possibly some of the following ones as well) because of increased dwell time. This is due to the extra passengers who have arrived at the downstream stations during the original delay.

6.2 Vehicle Halt and Passengers Off-Loaded

Sometimes, when a vehicle halt occurs, the train is severely enough affected so that it can no longer continue carrying passengers. In this case, it is brought to the next station, if possible, and the passengers must then get off and wait for the following train. Of the possible causes given above for a vehicle halt, the various malfunctions of the vehicle can lead to an off-load situation, but the wayside malfunctions (unless catastrophic) and the delayed start from the terminal cannot.

The effect of an off-load is similar to that of a vehicle halt, only worse. It is worse for several reasons:

1. The time spent to unload the passengers increases the initial delay to the affected train.
2. The extra passengers added to the next station create increased dwell time for loading passengers onto the following trains.
3. The momentary increase of system capacity at the end of the delay period is decreased by one train, since the delay causing train is removed from service.

6.3 Vehicle Slowdown

A vehicle slowdown occurs when a malfunction or other incident does not stop a train, but causes it to proceed more slowly than at its proper scheduled speed. This can be caused by a malfunction in the train such as the propulsion system, or car-borne signal devices, by a motorman who is running the train at too slow a speed, or by increased dwell time at stations due to heavy demand, passengers holding doors open, etc.

The effects of a vehicle slowdown are similar to that of a vehicle halt, except that, where the full effects of a vehicle halt are felt immediately, those of a vehicle slowdown build up gradually:

1. There is an accumulation of delay to the affected train; this delay reaches a maximum at the end of the run.
2. Following trains may be forced to slow down. The first following train will begin to be delayed when the delay of the affected train reaches h (where h is the difference between normal headway and minimum safe headway), the second following train when the delay reaches $2h$, etc.
3. Passengers at downstream stations will be delayed. The further downstream they are, the greater their delay at the station. Of course, they incur additional delay after they board because of the slow speed.
4. There is a momentary increase in system capacity for downstream stations as the affected train reaches them.

This increase begins when the first following train becomes delayed, and increases as more following trains are delayed.

5. There is a delay due to increased dwell time caused by extra passengers arriving at downstream stations. This delay increases as the affected train proceeds further along at its reduced speed.

6.4 Slow Point on Wayside

A "slow point" on the wayside is a point where trains must stop for a period of time before proceeding, proceed through at a slow speed, or both. A slow point may be caused by a malfunctioning wayside signal, the presence of a work crew on or near the track, an improperly set or difficult-to-change switch, or a defect in the track. A slow point which is repaired before it has affected more than one train may be treated like a vehicle halt, but otherwise it must be treated differently.

The effects of a slow point are:

1. There is an initial delay to the first train until the slow point can be diagnosed and "key-by" measures established to get trains past it. This delay has exactly the same effects as the vehicle halt described earlier.
2. Each succeeding train incurs a "key-by" delay, i.e., the amount of extra time necessary for the train to pass through the slow point. For a faulty signal, for example, this is the time required for the previous

train to leave the block served by the bad signal (if it is still there when the succeeding train arrives) and for the block to be visually cleared by a starter or dispatcher, plus the extra time required by the fact that the train must proceed through the block at a slow speed.

3. If the key-by delay is greater than the difference between the normal and minimum safe headway, trains will arrive at the slow point faster than they can leave it, and a queue will form. Each train in this case will incur a queueing delay (which increases with successive trains) in addition to the key-by delay.
4. If the key-by delay is less than or equal to the difference between the normal and minimum safe headway, passengers waiting at downstream stations will experience no delay other than the one incurred by the first affected train. However, if the key-by delay is greater, then the downstream passengers will continually experience a delay equal to the difference between the key-by delay and the normal headway.

6.5 Deleted Run

An obvious cause of a delay to passengers is the deletion of a scheduled run, either because of an insufficient number of vehicles available at the start of the day, or because a failure causes the removal of a train and there are no more spares to replace it. If no adjustment is made in the schedule, then all passengers arriving at stations, at a time when they would ordinarily use the deleted run are delayed by an amount equal to the normal headway. However, the usual procedure at the MBTA is to adjust the schedule by advancing the departure times of several trains which follow the deleted run so as to even out the actual headways rather than to leave one big gap. In this event, all passengers who are picked up by the adjusted trains and also the first unadjusted train thereafter are affected. Their delay times would be successively higher multiples of the normal headway divided by the number of trains adjusted plus one. For example, if the next two trains are adjusted, the first adjusted train would appear to passengers to be delayed one-third the normal headway time. The next adjusted train would appear to passengers to be delayed two-thirds the nominal headway time. This again assumes the minimum safe headway is smaller than the normal headway by at least a factor of four, as in the example of Section 7.0.

6.6 Catastrophic Delay

Once in a great while an incident occurs which inflicts very large delays on the system. Examples of such incidents are fires, suicide attempts, extensive track damage, derailments, floods, and power failures. When this happens, what the MBTA usually does is to remove the passengers from the affected area as expeditiously as possible, and then set up shuttle buses to bridge the closed section of the line.

Once the shuttle bus service is operating, the effects on the passengers are that those who need to use the buses are delayed by a total of the amount of time needed to reach the buses and wait for them to arrive and leave, the difference between the travel time of the buses and the normal travel time of the train, and the time needed (for those who continue beyond the affected section) to reach the trains and wait for them to arrive and leave.

The delays incurred before the shuttle bus service starts is more difficult to calculate. However, it can safely be said that all passengers attempting to use the system at all until the shuttle bus service operates, plus all those attempting to reach or cross the affected section thereafter, will incur delays which will be intolerable to them.

7. EXAMPLES OF INCIDENTS AND THEIR EFFECTS

Following are ten examples to illustrate the various kinds of incidents discussed in the previous section and the effects they have on system performance. Note that the examples include two common responses the MBTA uses for delays; expressing trains past stations where they would ordinarily stop, in order to shorten a delay-caused gap in service, and crossing a train from one direction to the opposite one (after unloading the passengers) also in order to fill a gap in service time.

Assumptions

4-minute normal headway

1-minute minimum headway

4 stations at or after delay point; Stations 0, 1, 2, and 3. Station 3 is the terminal station.

Normal dwell at stations approximately zero minutes

Dwell delays due to accumulation of delayed passengers are ignored.

<u>Incident</u>	<u>Train Delays</u>	<u>Station Delays</u>
1. 3-minute vehicle delay	Train 1 = 3 min.	Stations = 3 min. for each station
2. 7-minute vehicle delay	Train 1 = 7 min. Train 2 = 4 min. Train 3 = 1 min.	Stations = 7 min. for each station, triple pickup at end of delay.

3. 7-minute vehicle delay, passengers offloaded from Train 1 at Station 0 (offloading takes 1 minute)
- | | | |
|-----------|--------|--|
| Train 1 = | 8 min. | Stations = 8* |
| Train 2 = | 5 min. | min. each, double pickup at end of delay. Station 0 also has double load of passengers at end of delay |
| Train 3 = | 2 min. | |

*Station 0 has increased load due to local passengers leaving Train 1.

4. 7-minute vehicle delay, express Train 1 to Station 2 (this gains 2 minutes)
- | | | |
|-----------|--------|------------------------|
| Train 1 = | 5 min. | Station 0 = 7 min. (1) |
| Train 2 = | 4 min. | Station 1 = 8 min. (2) |
| Train 3 = | 1 min. | Station 2 = 5 min. |
| | | Station 3 = 5 min. |

- (1) - triple pickup,
 (2) - double pickup,

5. 7-minute delay, train is crossed over from opposite direction to Station 1, after 4 min. of delay
- | | | |
|-----------|--------|------------------------|
| Train 1 = | 7 min. | Station 0 = 7 min. (1) |
| Train 2 = | 4 min. | Station 1 = 4 min. (2) |
| Train 3 = | 1 min. | Station 2 = 4 min. (2) |
| | | Station 3 = 4 min. |

- (1) - Triple pickup,
 (2) - Pickup, 3 minute wait, then triple pickup.

6. Slowdown delay, 2 min. per station
- | | | |
|--|--|------------------------------------|
| | | Station 0 = 0 min. |
| | | Station 1 = 2 min. |
| | | Station 2 = 4 min. (double pickup) |
| | | Station 3 = 6 min. |

		Station			
		0	1	2	3
Train1	0	2	4	6	
Train2	0	0	1	3	

7. 3-minute key-by delay due to wayside mal-function
- | | | |
|------------|-------------|--|
| All trains | 3 min. each | Stations = 3 min. each for first affected run only |
|------------|-------------|--|

- | | | | |
|-----|---|---|---|
| 8. | 5-minute key-by delay due to wayside malfunction | Train 1 =
5 min.
Train 2 =
6 min.
Train 3 =
7 min.
Train 4 =
8 min. etc. | Stations = 5 min. each for the first run, 1 min. each for each succeeding run |
| 9. | Deleted run | | Stations = 4 minutes each |
| 10. | Deleted run, next three runs have their schedule adjusted (e.g., schedule of 5:00, 5:04, 5:08, 5:12, 5:16, 5:20 becomes 5:00 (deleted), 5:05, 5:10, 5:15, 5:20) | | Stations = 1,2,3 min. corresponding to the first, second and third following trains |

Obviously, for a longer normal headway (eight minutes, for example) relative to a one-minute minimum safe headway, the delay incidents listed above would have much less impact on following trains. If the normal headway is close to the minimum safe headway (one and one-half minutes compared to one minute for example), then the delay incidents listed above would impact proportionately more following trains.

8. POTENTIAL RESULTS FROM AN AVAILABILITY ANALYSIS

Once a system is analyzed along the lines outlined here, availability may be used to examine the system from the points of view of each of the various components of failure diagnosis and recovery, failure management and schedule adjustment, reliability, and maintainability. These examinations will lead to specific steps that can be taken to improve system availability and service.

8.1 Failure Diagnosis and Recovery

The most important part of quick recovery from a failure is quick diagnosis of the trouble and proper "first aid" to allow service to continue until the failed item can be sent to the maintenance yard for repair. The employees who are always at the scene of an incident at the MBTA are the motorman and guard of the affected train. They are well-trained in diagnoses and "first-aid" techniques (especially the motorman, who has a more intimate "feel" for the vehicle and its surroundings). They are also provided with good communications for assistance from the dispatchers and starter, so they can get their train going again in a short time, and less frequently require on-the-scene outside help.

8.2 Failure Management and Schedule Adjustment

After an incident has been diagnosed and cleared up by getting trains moving again, it remains to restore the system to near normal operation as soon as possible. Often, especially during peak hours, both the first few trains upstream from an incident point and the first few stations downstream from it will be crowded as a result of the delay. It is less desirable to have those trains stop at the crowded stations, especially when most of the passengers in the train intend to continue past the stations (as would be true, for example, if there were a southbound delay just before Park St. during the afternoon peak). Only a few passengers would get off, so only a few passengers could get

on, and the whole operation would entail a large further delaying dwell time. Therefore, it would be beneficial to express the crowded trains past the crowded stations and let the less crowded trains which follow pick up passengers at those stations, thus cutting down dwell time significantly and thereby allowing the system to more quickly resume normal operations.

8.3 Maintainability

It is important for the repair people at the maintenance yard to have a good knowledge of the incident that caused the failure as well as the past history of that particular item, since this will provide them with essential knowledge they could not obtain just from looking at the item itself. Therefore, there should ideally be better utilization of incident reporting forms through which the motorman, guard, and central control personnel can quickly give the appropriate details while they are still fresh in their minds. The forms must be easy forms to fill out and process; otherwise, too often the system breaks down as unworkable.

Additionally, these forms should be analyzed by engineering personnel and filed in an organized manner (possibly by means of a computerized data base) in order to detect trends in or groups of frequently occurring incidents.

8.4 Reliability

Every delay-causing incident traced to equipment failure is a potential reliability problem. The incident reporting forms and engineering analysis of similar incidents mentioned above are necessary to establish priority, and isolate the potentially most beneficial reliability improvement program actions. Since the first concern is understandably to get trains back into service as quickly as possible, the success of a longer term off-line reliability improvement program by its nature hinges on a stable and enduring incident reporting system to measure the relative benefits of changes. This is also true for measuring changes in maintenance procedures, operational procedures, sparing philosophy, training or any action taken in an attempt to improve overall system effectiveness.

9. Further Work

This report has described the formation of a qualitative availability model. Further work is needed to develop a quantitative assessment over a typical time sample. Among topics recommended for future work are:

1. Make specific calculations of MBTA system availability using sample data.
2. Incorporate demand data to form a passenger-oriented measure.
3. Develop a predictive model for MBTA system availability.
4. Investigate possible improvements in data management.

5. Investigate the effects of dwell time on system delay due to incidents.

10. REFERENCE

1. Heimann, D.; "Availability -- Concepts and Definitions"; Proceedings 1976 Annual Reliability and Maintainability Symposium; Paper #1402, pp. 482-490.

(End of Paper 6 Presentation)

Dr. Heimann's paper was followed by a sequence of comments, questions, and an exchange of procedural alternatives to the operations described in the paper.

Comment from Mr. Pawlak, TSC

I'd like to clear a point from Dave's description of his work, namely, that most of the work he has done has been with the rail rapid transit, which we typically classify as a conventional system. UMTA says MBTA is a conventional system, and therefore is entitled to capital assistance. I often think that AGT-oriented people overlook a lot of what is inherent in rail rapid transit system operation. Even in studying it myself, I have overlooked things that inherently have grown up through the years as techniques that are used. There are attributes of vehicle design that are habitually included in a specification as functional requirements that are extremely important for system availability. The availability analysis provides the operator with the capability for diagnosing a fault, cutting out a door, and cutting out a propulsion system, for example, to keep the train moving. It includes things which the operator can perform in two or three minutes to enable him to get the train to a terminal. It also includes things that an operator can do in a terminal to get the train back on line, or to determine whether the failure is serious enough to require committing the train to a shop for major repair.

If, however, in your modeling and in your analysis you cannot describe the availability performance of a "conventional" two track, line-haul, ten- or fifteen-mile system with on-line stations on trained vehicles, an operator on board, crossovers, etc., then I personally am not going to believe any of the analysis, or whatever you do, for more complicated networks. A key difference of conventional systems is the fact that you do have an operator on board. We talked about high levels of automation. In the last analysis, however, the operator is a maintenance diagnostician with certain tools and some ability to make repairs, and get the train moving again in those critical few minutes of time which, when you look at the total system,

do not seriously impact level of service. If it is a "forgiving" system, one that will permit 90-second headways while you're currently running four-minute headways, then you've designed in a certain amount of compressibility, or "forgiveness." This is what allows you to have fairly high levels of service. But if you're designing with very close headways, and there is no forgiveness in this system, then, when you do have a down situation, and you cannot repair it in those few seconds or few minutes, the delay ripples through whole system, and you have many people delayed. There's a lot to be learned from rail rapid transit systems for application to future systems. They're out there, and you can touch them and measure them, although sometimes it's pretty hard to measure them, as Dave's found out. As we saw, only two out of eleven definitions for availability appear to be measurable.

Mr. Dickson

Art Dickson, Systems Technology. Have you developed a computer parts failure data base for MBTA?

Dr. Heimann

The development of the data base is a planned thing for this coming year. It's been recognized at the outset that it's necessary to develop the data base. So, the first thing that we looked into on the MBTA had to do with the data they were keeping, as already described.

Comment from the Audience

Lou Frasco, TSC. When we got on the MBTA property, we were called in to do a study and evaluation of some things on equipment they had on the Red Line. We've done that, made some recommendations, and are about to enter a performance monitoring mode. We're getting to where we have begun to scrutinize carefully the vehicle failure defects reported in some of the wayside systems. We have begun placing some order into them, dissecting the system, and making some recommendations as to what kind of failure reporting procedures should be used. That's one of the weakest links in being able to trace our way through this process.

Dr. MacKinnon

Is the MBTA planning to implement any of your suggestions?

Mr. Pawlak

Two specific recommendations were made. One has already been implemented. The other is in the process of being implemented, but it won't really show its true worth until the winter time. The first one had to do with signal levels of the train control system at the interface between the wayside and the vehicle. These have been changed in the way of maintenance procedure, and there's been a significant movement in reducing the number of bad train order situations.

The other one had to do with environment in the train control equipment underneath the car. There were winter-related problems around 32°, and we won't see that state for another couple of months, hopefully.

Mr. Frasco

Those are hardware matters. In this workshop we are discussing service level availability measures. In the performance monitoring mode we must identify the data needed to allow us to evaluate the impact of the recommendations. We are dealing with MBTA management personnel who are looking for some evidence of whether or not there have been improvements. On the basis of our experience we will recommend to MBTA measures that they can use to assess how well they're doing in some of these areas.

Mr. King (BART)

Keeping to the question of definitions, what meaning shall we attach to availability? I've heard some interesting opinions on the subject this morning, and I feel that people are thinking in the right direction. But I believe that what we're really looking for is an industry consensus. At present we all seem to be clinging to our own separate concepts of availability and, in substantiating our thinking, are saying of others, "They didn't do it right." But the problem here is that "right" has not been

defined. I believe if somebody can come up with a technique for attaining this industry consensus, then money will become available for us to obtain the necessary data to achieve the goal inherent in the definition. I urge that the thinking continue on this aspect.

Dr. Heimann

This program has two elements. One is to talk to various properties and find out how they are defining their service availability; the other is to get the information around to other parts of the industry through the contacts that we have. At the same time, we are trying to develop the framework in which to have such a discussion.

Mr. King

Dave, I think that one of the things that the task force can come up with is an industry consensus from the operating standpoint. Another thing I wanted to ask Bob Pawlak. You identified the operator as a diagnostician. Are you then evaluating the MBTA in terms of its operators as control tools?

Mr. Pawlak

We know the good ones from the ones that are not so good. In the sense of evaluating, that's part of the problem.

Mr. King

Is there any way you measure that?

Mr. Pawlak

From the data that is presently being collected, one can tell whether a train has arrived at the terminal on time or late; if it arrives late, one can look at the incident log and figure out what happened. The log does identify the motorman but beyond that you have to get the dispatcher's evaluation of the motorman's abilities, or make comparisons of similar incidents to determine whether the delay time on his part was inordinately long compared to normal. We don't really have complete knowledge on the impact of the motorman on this, but it's definitely something that needs

looking into, especially on the manual systems. On the automated systems, the equivalent problem relates to operation of ATS in quickly identifying and correcting incidents as they come up. Whereas in the manual system it is essentially a human factors psychological study, in the automated system the evaluation problem is of the type you would encounter in the AGT project. It's a technical, software kind of discussion that has in the past lent itself readily to analysis.

Mr. J. Korman (New York City Transit Authority)

In reference to a fully manual system, which is basically what we've got in New York, we have a training program for people whom we call our test train managers, and who are responsible for the movement of all trains within a division. For the most part, we've got a very flexible railroad as far as being able to cross trains from a local track to an express track is concerned.

Aside from the 2,000 or so people who happen to be on the train that has a problem, it's even more important to keep the train behind it moving because each of those has 2,000 people on it. Fortunately, we are not faced with a major problem more than twice a year. We have set up a training session for train managers, whom we actually seat at a mockup of their command center console. We have three people in the back room "calling the shots." They will "shoot out" whatever the situation is from the start of a problem. A motorman might call in that his brakes are on emergency; these three people will then carry out whatever instructions the trainee gives them. They can vary the script (from a series of about 22 scripts) for various degrees of difficulty, depending on how long the man has been a train master. We've had great success and put through approximately 200 people as test train masters. We then downgraded the difficulty of the problem for the test train managers' assistants, who are called radio dispatchers. In a number of cases, the incidents, when they were written, were pure fiction, but later some of them have actually happened! So, by referring to the

scripts, we solve the problem, mainly because the people who wrote the scripts were very knowledgeable, and took several days to work out each of the detailed solutions to the problems. Of course, when the thing really happens, you've got to make a decision within a period of four minutes as to what you're going to do with the train. So, it's a very successful type operation.

Dr. Heimann

Definitely, dispatchers and motormen in such a system are very, very important. They're the difference between good availability, even with relatively poor equipment, and very bad availability, when one doesn't know what one has to do when an incident occurs.

Mr. Siddiquee (SRI)

A brief comment. It was very enlightening for me to hear these speakers. We've talked about service availability from the point of view of the user, about availability from the aspect of the operators, and about the costs. I think what needs to be done is to be able to translate the user availability to the system availability and methodology, and the system availability into costs. There needs to be some methodology to translate user reliability requirements into system requirements. There's still something needed to complete the loop.

Dr. Heimann

Definitely, that remains to be done. What we must do this coming year is to identify the structural interrelationships, and get them quantitatively linked up.

Comment from the Audience

Just a quick comment on Dave's approach. The fact is that he is identifying, starting with an overall number, and going down to assignable causes. This is a good way, I think, of handling an index, because what we've really looking at is

unavailability. We're trying to get rid of unavailability, unreliability, and undependability. We're attempting to home in on the unavailable part, dig down and find out the causes of unavailability, categorize them, and try to get rid of them.

Dr. Heimann

I think unless we can develop analytical procedures to relate the service availability to actual component characteristics, we aren't going to be able to make a lot of progress in improving our transit systems.

Dr. Anderson (University of Minnesota)

Dave, you mentioned that there's a lot more data acquisition in BART than in MBTA. Have you been able to make any case to the MBTA that it would be worth its while to gather that and figure it up in terms of economics?

Dr. Heimann

Yes, I can make a case. But the people at the MBTA are interested in the problem themselves. So, we really don't have to make a case for it; they're in agreement. The only thing that now has to be done is to actually do it. My work until now has been to get an idea of what data the MBTA is now accumulating. We'll then determine what additional data is necessary, and try to get the data base going.

Mr. Aboudara

I'd like to emphasize what I said earlier today, that there is a two-year-old contract package which the operators have worked out with UMTA. We have defined the work statement to do the very thing that's being talked about. The operators are willing to sit down as long as they know it's a legitimate exercise. And apropos Jim King's statement, money happens to be a ruling factor here. So as soon as we can get this contract official, and we hope that it's going to be very soon, there will be a serious effort to do just the thing that you folks are asking for. We know, and the operators in industry know, that it is

necessary, and we want to do it. It's like anything else--it takes money. So, I want to reemphasize that we're ready to go. We've had the work statement and no criticism any place, but it's a very frustrating thing as any of you can realize. We know what we want to do; we want to go with it.

(End of Panel 1 Session)

PANEL 2

OPERATOR EXPERIENCE IN OPERATIONAL SYSTEMS

PANEL 2
OPERATOR EXPERIENCE IN OPERATIONAL SYSTEMS

Mr. Watt of TSC introduced Mr. J. William Vigrass of PATCO as chairman of the proceedings for the second panel session. His introduction was followed by Mr. Vigrass's opening statement, subsequent paper presentations, related question-and-answer periods, and discussions and comments from panel participants and the general audience. The session opened with Mr. Watt's statement.

Mr. Watt

The second panel this afternoon is going to represent the opinions and experiences of operators in operational systems. The chairman of this panel is Bill Vigrass, of PATCO-Lindenwold in Philadelphia. Bill is Superintendent of Equipment of PATCO-Lindenwold. His experience in this field is extensive. His background is in economics. He received an MBA Degree from Western Reserve University in 1963, and has completed two years of study toward a doctorate in Economics. He has been active on a number of industry committees, such as the Transportation Research Board and the Committee on Rail Transit, of which he is the chairman. He is a member of the Committee on New Systems Technology, the Light Rail Advisory Committee, and in APTA, the Automatic Fare Collection Committee, on which he also serves as chairman. Mr. Vigrass:

Mr. Vigrass

This afternoon we will hear the experiences of several operators chosen to represent some part of each of the facets of this field. The operators to whom I refer include: one conventional manually operated rail rapid transit system, the Chicago Transit Authority; BART, the Bay Area Rapid Transit System; two-airport-oriented AGT systems, two of the very few existing operational - AGT systems; and my own system, a high-speed line-haul transit system that we consider to be

semi-automated. We will be talking about various facets of availability as outlined in the TSC program. Each of us will endeavor to answer these questions as best we can from our own experience.

The first speaker is Mr. Don Ochsner, of the Dallas-Fort Worth AIRTRANS system. Don received a BS Degree in Mechanical Engineering from the University of Cincinnati in 1962, and an MS Degree in Solid Mechanics from Catholic University in Washington in 1967. From 1962 to 1967 he was a Test Engineer with the NASA Goddard Space Flight Center, and from 1967 to 1970 a Structural Dynamics Engineer with LTV Aerospace. From 1970 until today he's been with the Dallas-Fort Worth Airport, where he was Supervisor of Engineering during construction, with responsibility for the AIRTRANS contract. He is currently Manager of AIRTRANS, responsible for both operation and maintenance of that facility. So, he has considerable experience in coping with the problems we are talking about.

PANEL 2

PAPER 1

OPERATIONAL FEATURES OF THE
DALLAS-FORT WORTH AIRTRANS
SYSTEM

D. OCHSNER

OPERATIONAL FEATURES OF THE
DALLAS-FORT WORTH AIRTRANS SYSTEM

D. OCHSNER

Before discussing the specific subject of the panel, operator experience, I would like to present a short description of the AIRTRANS system as it is operating today. The data in table 1 indicates the item, the number involved in the system, and their respective characteristics, and additional statistical data peculiar to the AIRTRANS system.

TABLE 1. AIRTRANS STATISTICS

Item	Number in Use	Characteristics
Passenger vehicle	51	40 passengers per vehicle (16 seated, 24 standing) Rubber tire, puncture proof Fiberglass body, aluminum frame
Cargo carrying vehicle	4	No top Carries containers

TABLE 1. AIRTRANS STATISTICS (CONT)

Item	Number in Use	Characteristics
Concrete guideway		13 miles of guideway (80% at grade - 20% elevated) Two-foot-high parapet walls for guidance
Central control computer system	2	One on-line One backup for off-line work
Terminal process computer	5	Smaller units for com- munication with Central
Central control console and guideway schematic	1	Shows guideway routing and vehicles moving Color-coded lights for information reporting PA, radio communications, TV station monitoring
Merge switch	38	Positive entrapment with deflecting switch rail
Diverge switch	33	Positive entrapment with switch machine
Interconnecting pas- senger/employee route	9	This combined operation is characterized as follows:
Supply delivery routing scheme	1	Connects four terminals, two parking lots, and maintenance area with Central Commissary Separate passenger and employee vehicles and stations 14 passenger stations 13 employee stations 10 supply stations

TABLE 1. AIRTRANS STATISTICS (CONT)

Statistic	Number	Condition
Riders per day	18,000	Noon and evening passenger peaks Morning, afternoon and night employee peaks
Vehicle miles per day	16,500	Evenly divided between passengers and employees
Door operations per day	17,000	Includes vehicle and station doors Passenger stations have doors Employee stations are platforms
Switch calls per day	57,000	----
Operating time	-	24 hours per day, 7 days per week
Availability of system	-	98 percent during the last nine months. This means that 98 percent of the time people have been transported without the need for calling up backup buses.

That's the AIRTRANS system as it is operating today. Let me now review service and maintenance effort. An evaluation of service level begins with out Central Control logs, which are kept daily for each shift. These logs are used to record all service problems, and we keep a summary of those problems on a daily basis.

I'd like to go through some of the evaluation methods that we use to describe service level and maintenance effort. I've been challenged with the fact that the 98% availability really didn't describe how passengers are affected. So, I have developed a chart (Figure 1) to describe how we come up with a service package. I've chosen the month of August, which was a rather bad month for us, but even then it does illustrate the effort I'm making to describe the level of service for passengers. The chart is developed from our system control logs which our central control operators keep, on a daily basis for each shift, by writing down specifically what problems occur in the system. I tried to list the major problems that caused system interruptions, as you will note in the list at the left side of the chart. A few of the items listed may need some clarification, so I'm giving you a bit of additional description. The AAU at the top is the Automatic Announcement Unit. This is the tape used to announce what station is coming up. The second column is a service factor which I've arbitrarily assigned to the unit to get some feel for how these things affect passengers on their trips. Obviously, a tape announcement has an effect, but it's not very much of an effect, so I've given it a service factor of 1.

CPU is the Central Processing Unit, the central computer. Before we had the backup system we gave it a much higher service factor, but, now that we have a backup computer, it's a matter of switching in another computer. In fact, people don't even realize it when it occurs.

Going on down the line we see that the stopping matters have rather large service factor numbers. The bypass, for instance, is an actual bypass of a station by a vehicle, causing people to have to go all the way back and around, and resulting in an extra 15 or 20 minutes for them to get to their destination. So, it has a service factor of 15.

AIRTRANS SERVICE REPORT AUGUST, 1976

MALFUNCTION	SERV FACT	AUGUST, 1976																													TOTAL					
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29		30	31			
AAU	1	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///		
CPU	1	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///		
OTHER TPU	3	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///		
6W TPU	3	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///		
RESET. SPD. BROACH	1	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///		
NONREST. SPD. BRCH.	5	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///		
AIR CONDITIONERS	1	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///		
STOPPING		///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///		
Bypass	15	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///		
Long	5	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///		
Short	4	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	
Veh./Station Doors	5	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	
PROPULSION	10	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	
SWITCH		///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///
Malfunctons	5	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///
Pseudos	1	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///
UNSCHEDULED DOORS		///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///
Equipment	5	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///
Passenger	5	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///
2W FALLING OBJECTS	2	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///
DOWN BLOCKS	10	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///
TURNSTILES	1	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///
SUPPLY	1	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///
B. U. ALERT/MAJ. DLYS.	Min.	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///
BUS CALLOUTS	Min.	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///	///
SERV. DAILY TOTAL*		269	187	110	99	112	103	56	165	159	144	100	163	211	426	408	85	199	190	101	75	85	112	91	125	51	61	68	73	116	156	284	116			

FIGURE 1. TYPICAL AIRTRANS SERVICE REPORT

On down the line you see switch malfunctions with a service factor of 5; this applies when a switch itself actually malfunctions, and you have to manually operate the switch. Switch pseudo is just an indication that there was a wrong switch call, that the vehicle stops momentarily, and that a central control operator sets the switch in the proper direction and it moves on; it does not have a major impact, and the service factor number is low.

Scheduled doors fall in the category of Class I malfunction on a vehicle. This malfunction involves equipment or passengers, and sometimes a combination of both, since a passenger on board can pull the door handle and cause the vehicle to dump. In this case, somebody has to go to the vehicle, reset it, and move it out.

Downblocks refers to a breakdown in the block control system. If we lose block control, then trains will not proceed through that block until it's corrected. This malfunction has a service factor of 10.

The bottom two lines are bus alert and major delays. Generally I use just minutes on those situations. We log major delays only if they're more than 10 minutes long.

The last item in the list refers to bus callouts. When any malfunction develops and the defective vehicle cannot be restored to duty in less than 15 minutes the backup buses have to be called into service.

Figure 5 shows graphically the daily totals of malfunctions occurring during the month of August 1976. This graph is primarily utilized as a management tool for self-analysis of service, and is a good way of showing others how good or bad service has been.

Let's look at the types of information given in the chart (Figure 1) and graph (Figure 2), respectively. The chart provides a day-to-day basis for each one of the happenings, mostly by the service factor. The service factor is basically a personal assessment, and does not always have a very significant meaning.

AIRTRANS SERVICE REPORT

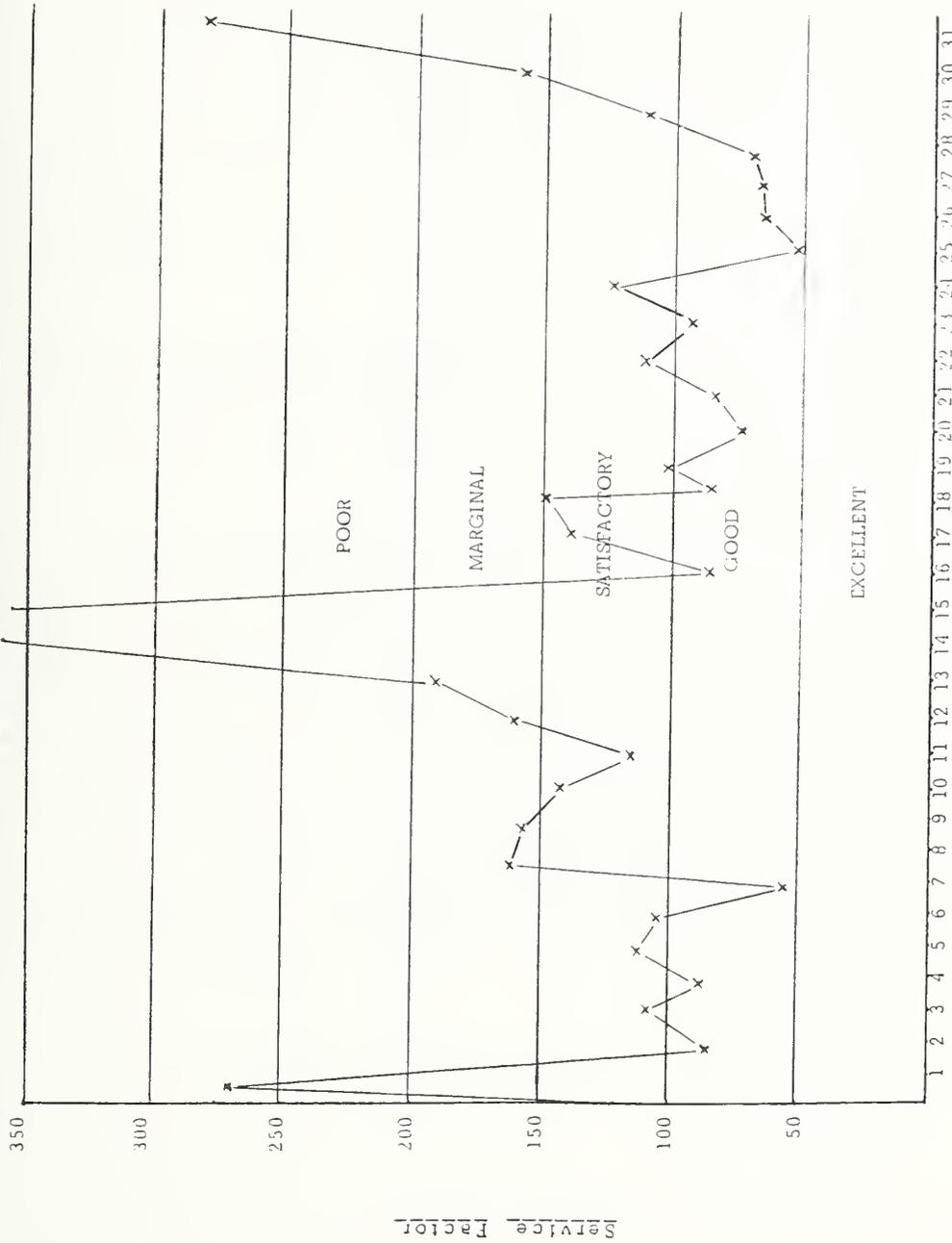


FIGURE 2. GRAPHICAL PRESENTATION OF AIRTRANS SERVICE REPORT

For instance, if you check the items at the bottom of the chart, you will note that the service factors have no specific value, but just indicate an assessment that there chances of occurring are minimal. On the other hand, the graph shows specific totals of malfunctions for the corresponding days of each month. In this way, it is more feasible to establish a grading of daily performance, such as excellent, good, marginal, etc., and easier to distinguish routine service from major interruptions. This is illustrated on the graph by the three major spikes. One was caused by a locked-up gear; the second by electrical conduit shorting because of sewage that got into it; and the third by a flooded guideway.

We have provided graphs of the type described for the last three or four months. In each case the graph appears to provide a satisfactory summary of the AIRTRANS service as well as a quick indication of how good the service has been.

The reports that you've seen are good for determining operational service, but they're not sufficiently detailed to provide reliability information for maintenance. Our maintenance work is tabulated on what we call the Maintenance Report (Figure 3). This report was developed by the Vought Corporation when it was doing operation and maintenance, and we still use the report form. In this report we tabulate, first of all, the discrepancy that is logged when it happens on board the vehicle. Later, when that particular item or vehicle is taken to the maintenance area, the detailed discrepancy and the action taken on that discrepancy are recorded in allotted spaces at the bottom part of the report form.

We keep the reports in our maintenance record files at present, and reliability data could be derived from the individual maintenance reports.

I will describe one more report that we use at AIRTRANS, the cost-data Monthly Statistics report (Figure 4). I've been tabulating the cost data since April of this year. Our January,

airtrans

MAINTENANCE REPORT
SYSTEM RESTORATION

PAGE 1

No. 59437

Col 8

1

DATE 27/5/76	ITEM NO. 11000	VEHICLE NO. PL2	LOCATION 3ESLO8	WHAT FAILED UTBCWG	ORIGINAL DISC. MR NO.
OCCURRED DURING					AIRTRANS MAINT. ADM.
<input checked="" type="checkbox"/> Service In "Service" Complete <input type="checkbox"/> Ready Track <input type="checkbox"/> Test (ATC, DT) <input type="checkbox"/> Inspection <input type="checkbox"/> Maintenance <input type="checkbox"/> Other					Warranty <input type="checkbox"/> Vandalism <input checked="" type="checkbox"/> Neither
AFFECTED MOVEMENT/CONTROL		VEH. REM.		PROB. CAUSE	
Yes No Call Received 3:00 Maint Arrived 3:05 Clear. Received 3:10 Sys Restored 3:10		<input checked="" type="checkbox"/> Reset Sw <input type="checkbox"/> Manual <input type="checkbox"/> Towed		<input type="checkbox"/> Vandalism <input type="checkbox"/> Accident <input checked="" type="checkbox"/> Normal Op	
DISCREPANCY					INITIATOR NAME
TRAIN STOPPED - CLI - SPEED BROACH					J.D. Morgan
MANHOURS Work Performed By Supervisor Date Completed					COMPLETED BY R&M AT HM DC FT R F M 65-66 67 68 69 70-73

A

B

VEHICLE OR FIXED EQUIPMENT REPAIR

2

ITEM NO 11MA7	PART NUMBER 31038-31GR1	SERIAL NO REMOVED 240	SERIAL NO INSTALLED 293
------------------	----------------------------	--------------------------	----------------------------

EQUIPMENT DISCREPANCY

C

D

E

F

G

H

I

J

K

L

M

N

O

FOUND AVO, A-11 BOARD, R-10, OUT OF ADJUSTMENT.

ACTION TAKEN (DISPOSITION)

Re-Adjusted A-11 PCB, Pot R-10 to READ 24 VDC ± .010 PER SPECIFICATION.

TEST RIDE OF VEHICLE INDICATES PROPER OPERATION. RELEASE FOR REVENUE SERVICE.

RELATED MR NO 59432	R&M CODES AT HM								
NON-REPAIRABLE PARTS	MANHOURS								
<table border="1"> <thead> <tr> <th>ITEM NO REF DES</th> <th>PART NO</th> <th>QTY</th> <th>NAME OF PART</th> </tr> </thead> <tbody> <tr> <td></td> <td>N/A</td> <td></td> <td></td> </tr> </tbody> </table>	ITEM NO REF DES	PART NO	QTY	NAME OF PART		N/A			Elapse Time 1.0 MANHOURS 1.0 Supervisor: J. Morgan Date Completed: 5/22/76
ITEM NO REF DES	PART NO	QTY	NAME OF PART						
	N/A								

MAINTENANCE

FIGURE 3. MAINTENANCE REPORT

AIRTRANS PASSENGER & EMPLOYEE SERVICE
MONTHLY STATISTICS
1976

	April	May	June	July	August	Sept.	Oct.	Nov.	Dec.
<u>Operations Cost:</u>									
Labor	24,495	25,609	21,314	24,698	24,648				
Power	13,399	17,893	19,211	22,090	22,798				
Sub-Total	37,894	43,502	40,525	46,788	47,446				
<u>Maintenance Cost:</u>									
Labor	119,844	112,923	98,081	123,046	98,755				
Materials	46,423	65,797	45,092	44,545	52,125				
Sub-Total	166,267	178,720	143,173	167,591	150,880				
<u>Associated Costs:</u>									
Rel. Impr/Contr. Support	6,442	4,261	5,980	4,035	9,508				
Fac. Maint.	23,726	27,173	16,671	20,013	14,975				
Pas. Serv. Agts.	36,894	27,937	27,427	30,862	27,058				
Sub-Total	67,062	59,371	50,078	54,910	51,541				
<u>Debt Service</u>	266,248	266,248	266,248	266,248	266,248				
<u>TOTAL COSTS:</u>	537,471	547,841	500,024	535,537	516,151				
<u>Revenue</u>	126,960	122,425	139,822	138,511	135,276				
<u>Net Costs</u>	410,511	425,416	360,202	397,026	380,875				
<u>Vehicle Mileage</u>	333,210	322,281	333,658	319,384	339,141				
<u>Ridership</u>	505,267	493,574	548,705	558,294	535,353				
Maint. Cost Per Mile/Passenger	0.58	0.55	0.43	0.52	0.44				
O & M Cost Per Mile/Passenger	0.33	0.36	0.26	0.30	0.28				
O & M & A Cost Per Mile/Passenger	0.61	0.69	0.55	0.67	0.58				
Total Cost Per Mile/Passenger	0.40	0.45	0.33	0.38	0.37				
Net Cost Per Mile/Passenger	0.61	0.87	0.70	0.84	0.74				
	0.54	0.57	0.43	0.48	0.47				
	1.61	1.70	1.50	1.67	1.52				
	1.06	1.11	0.91	0.96	0.96				
	1.23	1.32	1.08	1.24	1.12				
	0.81	0.86	0.66	0.71	0.71				

FIGURE 4. MONTHLY STATISTICS REPORT

February, and March data was not indicative, because we of the airport board had just taken over the system maintenance during that time, and we had a lot of initial costs in the first three months.

Starting with April 1976, the monthly statistics report format provides data on our operational costs, including labor and power; maintenance costs, including labor and materials; associated costs, including particular needs to be met from time to time. In the case of AIRTRANS, I have listed the following associated costs:

1. Reliability, and contractor's support. These costs include the usual reliability efforts and contractor service requests to support AIRTRANS.
2. Airport facilities maintenance. This cost is for cleaning passenger stations and cleaning around the guideways.
3. Additional support items for AIRTRANS which supplement the AIRTRANS maintenance costs listed above.
4. Passenger service agent's costs. These include the labor expenses of passenger service agents at passenger stations. The agents help passengers with flight information and, in addition, drive backup buses when the need for this service arises.

The total AIRTRANS costs for the month are obtained from the report by summing the operations, maintenance, associated, and airport service costs. Then, knowing the total monthly revenue for AIRTRANS rides, we subtract the revenue from the total cost to arrive at the net cost.

Additional data on the report includes vehicle mileage and ridership for the month. With this information, plus the costs and revenues already discussed, it is possible to calculate, and list the remaining data for costs per passenger and costs per mile.

An evaluation of the operations and maintenance costs per passenger and per mile indicates that, in our case, while the cost per passenger is moderately adequate, the cost per mile looks very good.

To summarize, AIRTRANS is a busy system in terms of equipment utilized, and we are accumulating a large quantity of data which will become increasingly important to the transit industry.

(End of Paper 1 Presentation)

Comment from the Audience

I want to call to the people's attention the fact that, according to Don, the current O&M cost per vehicle mile is 58 cents. That's about two to three times less than the cost you would find in most transit systems in the country.

Mr. Frank Smith

I wonder why the cost is half, or even less than half, of the usual transit system costs?

Mr. Ochsner

No drivers. That's where the cost is.

Mr. Vigrass

That's what we're really talking about, automation. And it works. Well, thank you, Don. I think your system, of all the ones that are running now, most approximates a real transit common carrier. Your system is complex; it has many vehicles and many switches, and you offer a variety of services. I think you've accumulated some real data, although perhaps not as much as you or the people participating here would like. But I think you've got a good handle on it, and a good beginning.

Our next speaker is from another airport. Max Bitts is from the Seattle-Tacoma Airport, a part of the Seattle municipality, also referred to by the acronym SeaTac. Max was appointed in 1972 to the position of Electronics Systems Superintendent, a position he still holds today. He's in charge of electronics systems of both the trains and the environment, whether at waysides or stations or on the main line. He holds a BSEE Degree from the

State College of Washington. He has been an electrical contractor, and he also worked for 13 years at Boeing and 12 years at Westinghouse. In addition to these activities, he served as a reservist with the Corp of Engineers from 1936 to 1969, and served on active duty during World War II. He will speak to us now about the SeaTac People Mover system, with which operation he has dealt in the most recent years.

Mr. Bitts

Thank you, Mr. Vigrass. I did not prepare a system description such as you got from the last speaker. I assumed that everyone here interested in this technology has access to a book which has a very good description of the Seatac People Mover. We now call it a subway, incidentally. The only change I'll make here is that we now have twelve cars instead of nine. The book I'm referring to is the OTA report titled "Automated Guideway Transit, An Assessment of PRT and Other New Systems, Including Supporting Panel Reports," July 1975. I think many of you probably have that, and I urge the rest of you to obtain a copy.

PANEL 2

PAPER 2

OPERATIONAL FEATURES OF
THE SEATAC (SEATTLE-TACOMA)
SATELLITE TRANSIT SYSTEM

M. K. BITTS

OPERATIONAL FEATURES OF THE SEATAC
(SEATTLE-TACOMA) SATELLITE TRANSIT SYSTEM

M.K. BITTS

SATELLITE TRANSIT SYSTEM

Our system went through an evolution period which started with the planning stage, followed by a contract award for vehicle manufacture, with a specified service availability goal of .998. The manufactured vehicles were incorporated in the Satellite Transit System (STS), and were subjected to a series of monitoring tests. This sequence, with specific events related to each of the above general activities, is included in the progression of events contained in Figure 1.

GENERAL DESCRIPTION

We have two loop runs, with a shuttle between the two. Each of these loops serves one satellite. United Airlines uses all of one, and Northwest Airlines and all international airlines use the other satellite. The shuttle is an incidental convenience between the two loops. It's not necessary to get passengers

to the satellite; therefore, in our availability system we do not count the shuttle operations. As a rule, we leave the shuttle alone and let it run. It runs perfectly all the time, because it just goes away and comes to you. But we use it for training, and for various other things that really don't count in reliability. As a matter of fact, we have one car dedicated to this job and we take it out of service, put it in the maintenance area, and put it back in service a day later. The reason we don't replace it is that it has to be turned 180° and the antennas reconfigured. Thus, we save about four hours by adjusting the system when we need that amount of service.

I wish to mention that I came to Boston on one of the largest mass transit systems in the world. And I feel that the SeaTac Satellite Transit System (STS) is a feeder line for the transit system, namely the United Airlines and other lines of our great air transit system.

We always consider safety first. Whatever we do, if safety is involved, we handle that first, or we don't do what we had intended until the safety problem has been solved. I think the success of our system, is largely attributable to our preventive maintenance system. Our preventive maintenance documentation is in the Army format. The instructions of every page are carried out at least once a year. But nothing is done to the cars, short or repair work, unless it's documented in that manual.

A remark has been made: "Make sure there's some money spent to make the system work after it's been installed." I confirm that if we duplicated the SeaTac System and I had anything to do with it, I would insist on the manufacturer putting at least 25 percent aside, so that he and I could spend it as needed to make it work after he got it installed. I will say that when we demanded that, Westinghouse responded.

In the last six weeks before revenue traffic, we were confronted with a problem. We had a Vice-President who, besides insisting that we make the system work within the reliability requirements, looked for service at the station every two minutes.

The airlines, which pay for the system, for all the active services, and for the fine maintenance we assure them, want no more than one or two failures a year. For that reason, they will accept service at the station up to 15 minutes. We don't violate that specification ever, and we also don't use it very often.

I now present a statement on the SeaTac Satellite Transit System (STS), following which I will provide, in topical outline format, a series of data describing the STS operation. The data includes definitions of terms and expressions peculiar to the STS and, in addition, constraints within which the system operates.

Seatac STS is considered to be a vital link in providing uninterrupted service for 60 percent of terminal traffic to and from our north and south satellites (50 percent of aircraft gates). This link is the only means provided to reach the satellites, as they are surrounded by aircraft ramps. Only in emergencies are standby buses put in service to move passengers to and from the satellites. (This design concept was accepted, with the risks, as the solution to save the SeaTac location for 25 years additional lift.)

AVAILABILITY

Availability for this system is measured by service between the main terminal(s) and the satellite stations. The system availability is determined by the expression

$$\frac{MTBF}{MTBF + MTTR} ,$$

where MTBF = Mean time between failures (service interruptions)

MTTR = Mean time to restore service to the satellites

Availability Characteristics

The positive features and limitations of the system availability are listed in items 1 through 6 on the next page.

1. Defines the relative ability of hardware and personnel to accomplish the goal of service to satellites
2. Points out the dual approach toward correcting any service degradation
 - a. Improve PM (Preventive Maintenance), CM (Corrective Maintenance), or design
 - b. Improve recovery techniques
3. Does not provide measure of equipment availability for service
4. Does not provide prediction for rolling stock requirements
5. Does not provide comparison to other system using "repair" time
6. Does not provide basis for level of craft staffing.

MTBF and MTTR Characteristics

The parameters which determine the system availability also are identifiable by positive features and limiting characteristics. These are listed below.

MTBF

1. Defines the relative state of maintenance of equipment
2. Indicates the effectiveness of the PM and CM activities
3. Measures the intensiveness of system surveillance and supervision
4. Does not support maintainability studies. (Does not reflect any failures/parts replaced on equipment in scheduled maintenance or ready spares).

MTTR

1. Measures restorability
2. Measures the state of training and preparedness of recovery personnel

3. Provides basis for design changes aimed at improving time to restore
4. Does not provide indication of man-hours to repair discrepant equipment.

WESTINGHOUSE PARTICIPATION

Original reliability reporting covered 21 basic subsystems and three categories: MTBF, MTTR, and Availability. Because of the quantity (45 failures/month) and indeterminate nature of many of the failures, this monitoring system was declared by Maintenance to be unsuitable for long term use in determining availability. In March 1974 SeaTac Maintenance, on recommendation of Westinghouse, changed to the system used today, disruption classification.

Figure 2 shows the extent of Westinghouse participation during the period 1973-1976. The design and maintenance responsibilities gradually are reduced at the same time that the service availability continues to increase. The data below indicates additional information for the period extending to 1977 and beyond for Westinghouse participation.

1973-1975 - Total responsibility (with Port labor)

1975-1977 - Tech. rep. responsibility (2 each)

1977 and on - Minimum tech. rep. from Westinghouse.

DISRUPTION CLASSIFICATION

Disruption classification as applied to the STS refers to a method of failure (disruption) classification by type consistent with the statistically small sample of system disruptions experienced. This method of classification allows improvements to be evaluated and provides quick response by indication.

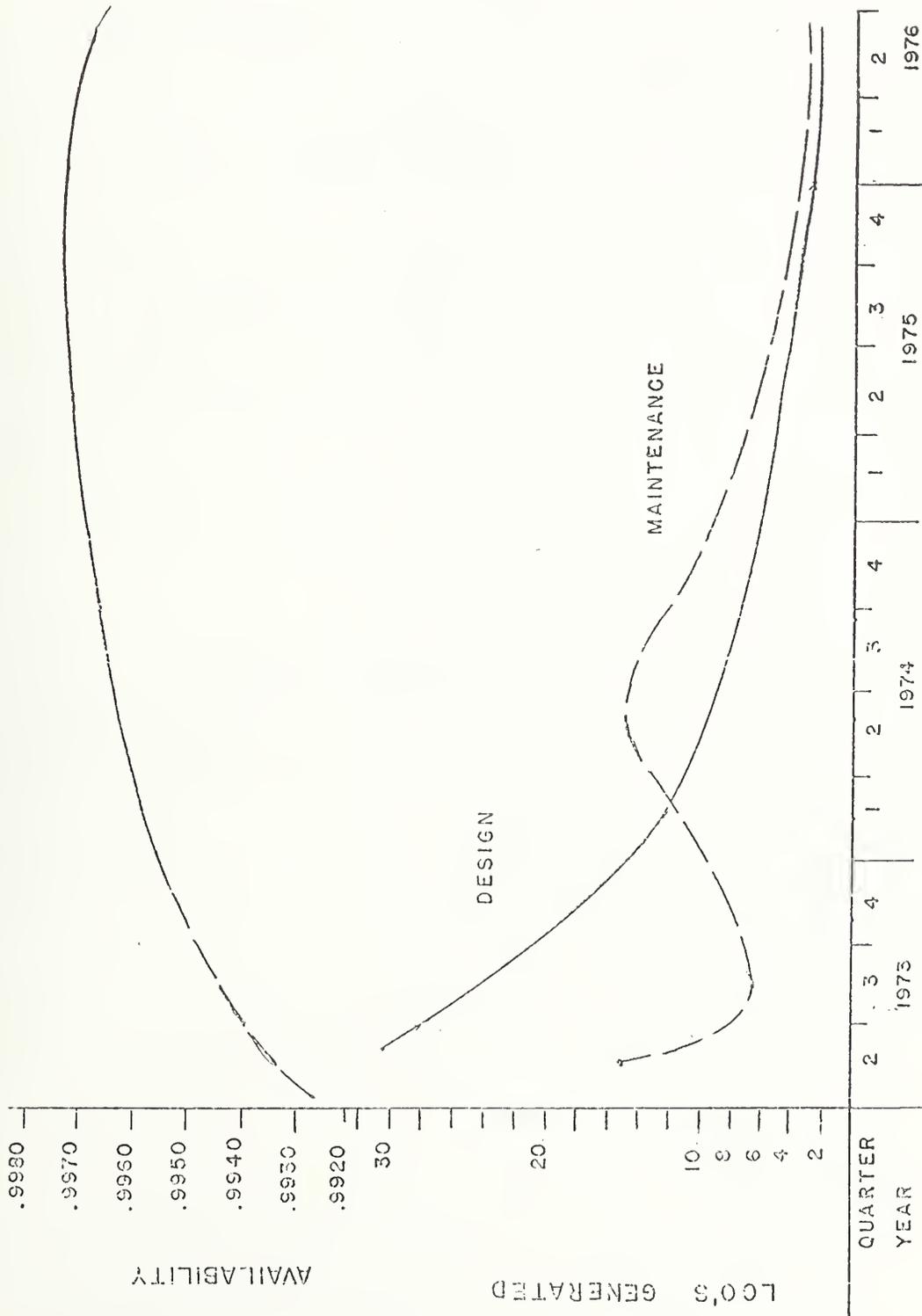


FIGURE 2. WESTINGHOUSE PARTICIPATION DURING 1973-1976

Types of Disruption Classifications

Four types of classification are used to identify system failure: random components, patterned, preventable, and intermittent. They are defined as follows:

1. Random Components - Disruption caused by a failed component positively determined to be the sole source of disruption
2. Patterned - Any group of "resettable" or self-correcting disruptions exhibiting similar modes of failure
3. Preventable - Any failure attributable to equipment not maintained or operated consistent with design specification
4. Intermittent - A single resettable or self-correcting disruption that lacks sufficient symptomatic evidence to be classified in 1, 2, or 3 above.

Disruption Classification Uses

Random Components - (20 percent of all STS disruptions)

1. Any dramatic increase in this category triggers a mass change out of parts or intensification of maintenance in the appropriate mileage or time-based preventive maintenance procedure(s).
2. Highly productive during start-up and early system operation; very static today.

Patterned - (50 percent of all STS disruptions)

1. Compensates for poor/small statistical samples by allowing data accumulation over extended periods
2. Category consists of repetition failures primarily due to
 - a. Latent design defects
 - b. Disruptions due to failed or failing components
3. Potential use: Ability to extract dependent or recurring failures from this category as an indication of system maintainability

4. Once the problem is isolated, there is no correction to failure coding - the patterned group simply becomes a dead file.

Preventable - (10 percent of all STS disruptions)

1. Primarily a measure of our maintenance effectiveness
2. Triggers immediate reaction - cause is known
3. Only disruptions caused by improper manufacture or maintenance are allowed in this category
4. Allows the monitoring system to define the maintenance learning curve.

Intermittent - (20 percent of all STS disruptions)

1. Measure of extent to which system is repairable.
2. Objective analysis of this category is not possible; the basic criterion is lack of information
3. Includes failures from three above categories; catch-all or operational techniques which are inconsistent with design.
4. Intermittents will anticipate an increase in random components.

GENERAL COMMENTS ON FAILURE MANAGEMENT SYSTEM

1. All inputs come from
 - a. Recovery personnel reports
 - b. Operations Department log/report
 - c. Computer print-out log
2. System designed for manual analysis
3. Each failure is reviewed weekly by a team consisting of a reliability engineer, recovery technician(s), and lead technician.
4. Data coded monthly and plotted - (approximately 45 disruptions/month)

5. Data is not corrected when true cause is determined; it goes to dead file
6. The four categories are normalized as percentages
7. MTBF, MTTR, availability figures are plotted by subsystem (N. loop, S. loop, Shuttle) to amplify operational causes of malfunction
8. Anomaly: Total number of FFR's (Field Failure Reports) has remained relatively constant over the past three years, while the patterned category has continued to disclose and allow correction of problems.

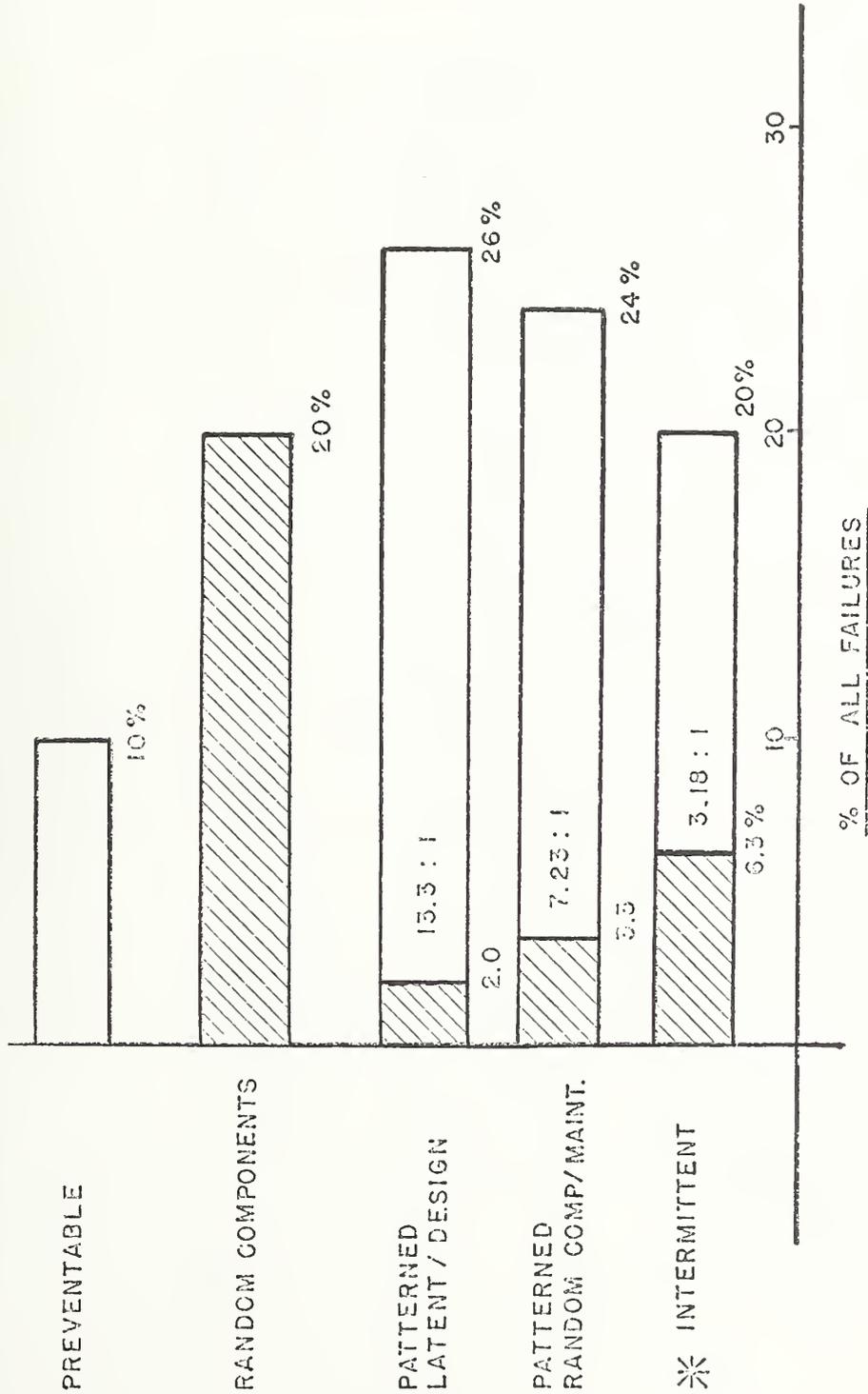
Explanation:

1. Every solution generally generates some additional problems.
2. Failures that weren't considered worthy of reporting initially are now reported.

Basic problem with automated systems reporting schemes: It is impossible, or impractical, to determine the actual lost service time of many auxiliary systems except as built-in annunciators are supplied.

Related Topics on Failure Management

1. Relationship of the above measures to hardware reliability and incidence of failure is indicated in Figure 3.
2. Effectiveness of failure management systems in reducing passenger delays is shown by the cumulative graphs of Figure 4.
3. Passenger delay measure of service availability is feasible with the SeaTac operation
4. The above steps relating to disruption classification provide an economical approach to the collection, definition, and analysis of necessary data.



 FAILURES AGAINST INHERENT HARDWARE RELIABILITY-31.6 % TOTAL ;
 DISTRIBUTION ESTIMATED-BASED ON DISTRIBUTION OF PREVENTABLE
 RANDOM COMPONENTS & PATTERNED.

FIGURE 3. BAR CHART RELATING FAILURES TO OVERALL HARDWARE RELIABILITY

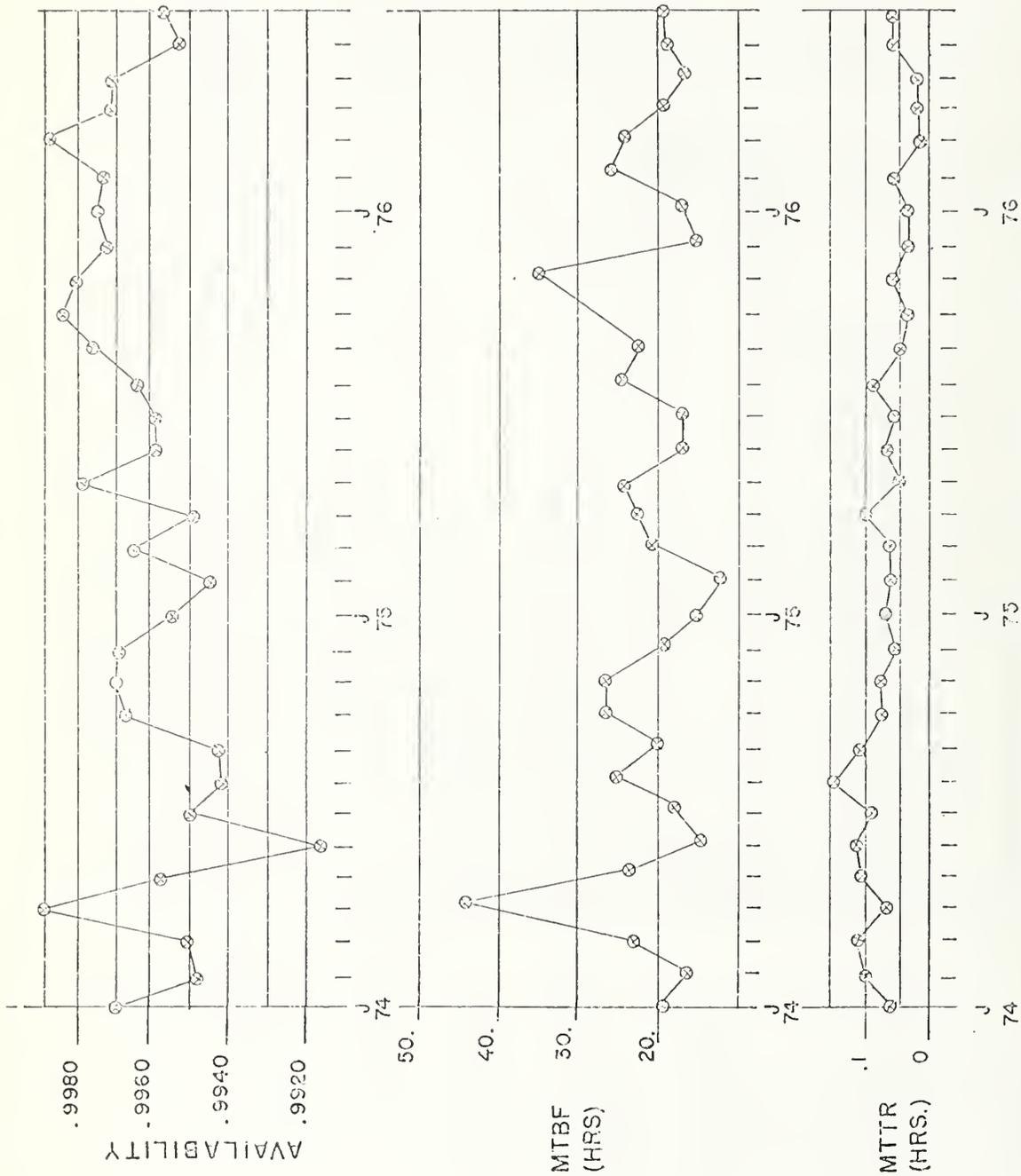


FIGURE 4. SYSTEM AVAILABILITY AND CORRESPONDING MONTHLY MTBF AND MTTR PARAMETERS (1974-1976)

Problems Involved in Data Collection

Three basic problems have to be considered by systems such as SeaTac:

1. Few statistical samples
2. Difficulties in identifying cause of disruption. This problem will be minimized by VDAS (Vehicle Data Acquisition System, discussed below under the topic heading VDAS).
3. The economics of a mature system is such that pure reliability data systems don't really reward the owner very much. The pure system depends on knowing exactly "what" caused the failure, and often this information is not easily obtained; it may be even guessed at, sending the effort off on a tangent.

SeaTac Maintenance is constantly seeking techniques or hardware to speed restoration and to isolate the problems, thereby reducing lost time and dollars. Presently, we are assembling an FCO (Functional Checkout) device, which will enable us to simulate the loop while standing in the maintenance area. In addition, we are pursuing the development of a vehicle data acquisition system (VDAS).

VDAS

VDAS is a device intended to serve as the equivalent of a technician onboard the vehicle, continuously monitoring sufficient key test points to allow positive identification of a defective subsystem on the first service disruption caused by that subsystem. It is the AGT equivalent of an airliner flight recorder.

The latest twenty minutes of data from about 32 test points will be stored in an electronic memory on-board the vehicle. After a disruption, a technician will board the vehicle and "dump" the contents of the electronic memory onto a portable tape recorder. The data on this tape will then be manipulated at the wayside to provide strip chart recordings of the 32 test points suitable for manual analysis by systems-oriented personnel.

(End of Paper 2 Presentation)

Mr. Vigrass

Thank you, Max. The next speaker will be Jim King, Reliability Manager of BART. Jim graduated from Case Western Reserve University in Cleveland with a BS Degree in Engineering Administration. He was formerly with the Westinghouse Transportation group in Pittsburgh, and for a time was specifically assigned to the BART activity at Westinghouse.

PANEL 2

PAPER 3

BART RELIABILITY AND AVAILABILITY
DATA EXPERIENCE

J. H. KING

BART RELIABILITY AND AVAILABILITY DATA EXPERIENCE

J. H. KING

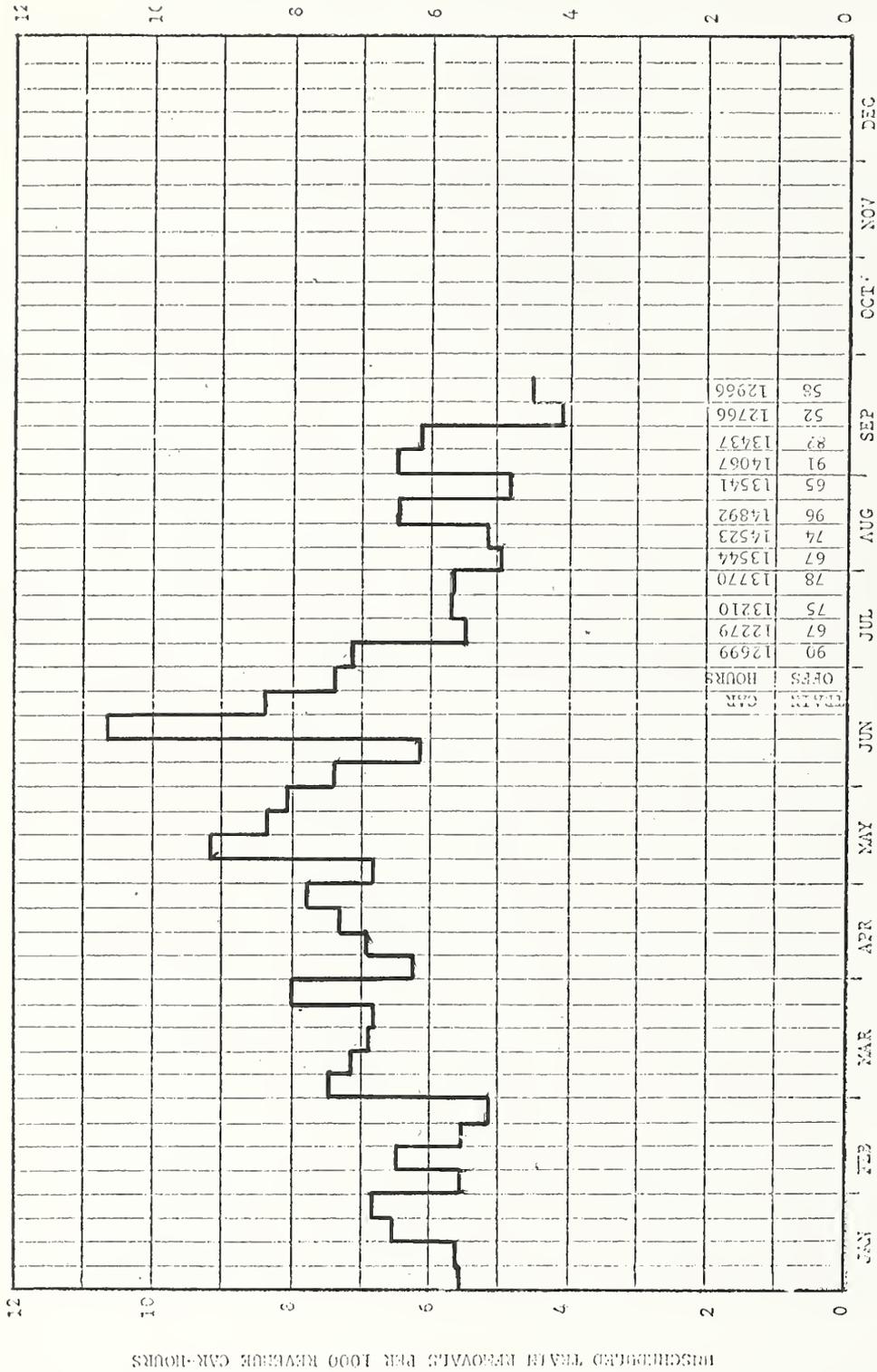
At the present time there are four fundamental evaluative criteria used on the BART system:

1. Number and rate of serious system delays (over 10 minutes) and their system-equipment causal factors. At the present time we experience about 100 per month (average of 5 per revenue day).
2. Number and rate of revenue vehicle equipment breakdowns which cause the associated train to be removed from service ahead of schedule. (Copies of the rates and subsystem breakdowns are shown in Figures 1 and 2.)
3. Number and rate of cars failed in revenue service. (Data on these criteria are shown in Figure 3).
4. Detailed tabulation of all actual equipment restoration actions. (A sample of such data is shown in Figure 4.)

In addition, data is taken in real time by computer entry on all revenue incidents on the vehicle and critical wayside systems. No system performance measurement technique can be perfect or universal. In general, we at BART are attempting to move toward those techniques which can help us to define two major areas:

1. Significant passenger delay incidents
2. The relation of system incidents to vehicle availability, and the causes of vehicle unavailability.

The primary problems are with evaluation of delay incidents. Delays may occur which affect only a single train, only one direction of a line, one or more lines, or the total system. The severity of such delays is largely a subjective decision.



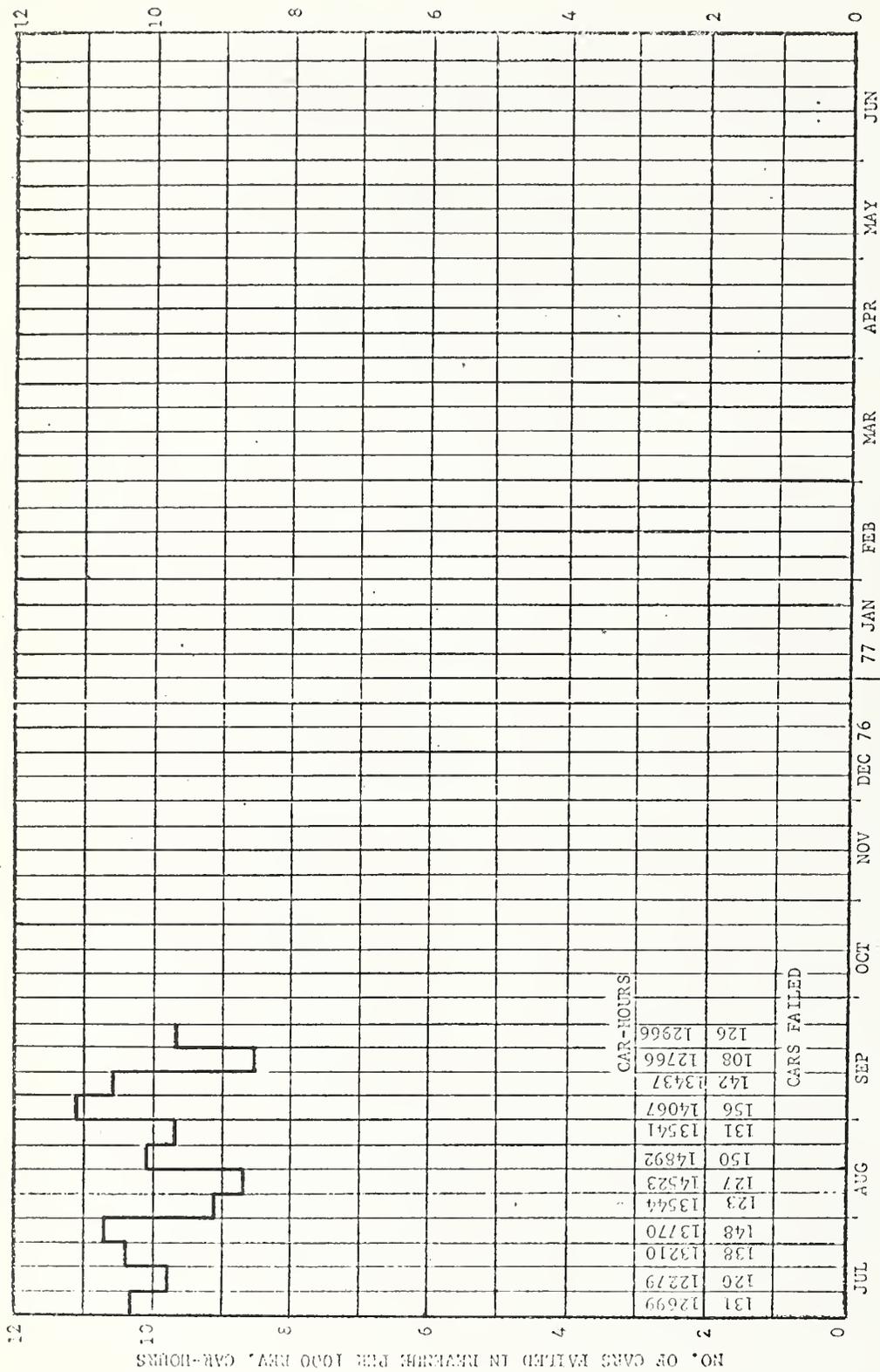
Source: Central Trouble Desk Morning Report & MFS Wkly Hr. & Mi. List, M99001 RELIABILITY ENGINEERING

FIGURE 1. WEEKLY UNSCHEDULED TRAIN REMOVAL RATE, 1976

TRAINS REMOVED FOR EQUIPMENT CAUSES -- BY CAR SUB-SYSTEMS
 (AVERAGES AND PERCENTAGES FOR FIRST 8 MONTHS OF 1976)
 SOURCE: CENTRAL TROUBLE DESK MORNING REPORT

SUB-SYSTEM MONTH	PROPUL- SION	FRICT. BRAKE	VEHICLE ATO	AUXIL- IARY	DOOR	TRUCK	BODY	COMMUNI- CATION	AIR- COND.	SUS- PENSION	TOTAL
January	97	94	56	28	17	7	8	2	6	3	318
February	98	68	39	23	17	7	3	3	2	1	262
March	167	75	65	43	19	14	5	7	-	7	482
April	175	79	65	33	21	11	13	4	3	2	406
May	202	83	60	42	12	14	6	3	3	-	425
June	219	68	52	45	19	10	8	4	7	2	434
July	141	75	42	28	23	27	2	5	2	-	345
August	142	71	55	42	23	6	4	3	-	4	350
8 month Total	1241	613	434	284	147	96	54	31	23	19	2542
Average	155	77	54	36	18	12	7	4	3	2	368
Percentage	42	21	15	9	5	3	2	1	1	1	100

FIGURE 2. SUBSYSTEM BREAKDOWN OF TRAIN EQUIPMENT



Sources: Central Trouble Desk Morning Report
 MPS Weekly Hr. and Mi. List, M99001

RELIABILITY
 ENGINEERING

FIGURE 3. WEEKLY CAR FAILURE RATES - IN REVENUE SERVICE

REPORT DATE 09-08-76
 PROCESS DATE 09-08-76 CYCLE 2

SAN FRANCISCO BAY AREA RAPID TRANSIT DISTRICT
 FAILURE SUMMARY REPORT
 EQUIPMENT GROUP/SYSTEM/SUBSYSTEM/COMPONENT
 FROM 07-01-76 TO 09-07-76

PAGE 02
 REPORT NO. 41000

GROUP 01 TRANSIT VEHICLES

COMPONENT DETAIL	FAILURE NUMBER	TROUBLE RPT REF	DAYS FAILED	LOCATION	ITEM NUMBER	E W R T S Y	SINCE ACQUISITN OPER-- HOURS-- MILES--	HOURS --TD-- REPR--	REMARKS
SYS 07 PDPULSION SUB 02 CONTROLLER 197 REVERSER	F874321	0746	07-07-76	0000545	2000105	1	0	0	1.0 CLEARED & ADJUSTED
REV XRC-432	F074331	0743	05-18-76	0000727	2000105	1	0	0	2.0 CLEARED CONTACTS
REV XRC-432	F065720		07-29-76	0000755	2000105	2	0	0	3.0 REBUILT ARMATURE
REV XRC-432	F062995		07-21-76	0000769	2000105	2	0	0	1.0 DISCONNECTED CAPACITOR

TOTAL FAILURES FOR SUB 02 --- CONTROLLERS

THIS PERIOD 49 LAST 12 MONTH AVERAGE 45

SUB 03 CONTACTORS
032 CONTACTOR

EQ1 UHD-609-A	F062717		08-08-76	0000571	2000106	2	0	0	1.5 ADJ AUX CONTACTS
EQ1 UHD-609-A	F055331	9555	07-28-76	0000504	2000106	1	0	0	6.0 ADJUSTED CONTACTS
EQ2 UHD-123-C	F070331		08-07-76	0000663	2000106	2	0	0	6.0 REPL
EQ2 UHD-123-C	F071931	0719	08-10-76	0000663	2000106	1	0	0	9.0 REPR & CLEARED
EQ2 UHD-125-C	F880321	8803	07-08-76	0000607	2000106	1	0	0	6.0 REPOSITIONED

TOTAL FAILURES FOR SUB 03 --- CONTACTORS

THIS PERIOD 5 LAST 12 MONTH AVERAGE 4

SUB 04 RELAY DRIVERS, CONTROLLER
071 DRIVER

R07	F062733		07-22-76	0000821	2000107	2	0	0	2.5 REPR
R07	F060327		08-27-76	0000313	2000107	2	0	0	2.0 REPL
R09	F024131	0241	06-04-76	0000316	2000107	1	0	0	2.0 REPL
R09	F064521	8845	07-05-76	0000654	2000107	1	0	0	4.5 REPL
R05	F031031	0313	08-08-76	0000708	2000107	1	0	0	5.0 REPL

TOTAL FAILURES FOR SUB 04 --- RELAY DRIVERS, CONTROLLER THIS PERIOD

5 LAST 12 MONTH AVERAGE 4

SUB 05 RELAY PANEL UCB 636D
032 CONTACTOR

SUC	F888721	8887	07-12-76	0000156	2000108	1	0	0	1.0 REPR
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FIGURE 4. TABULATED DATA OF EQUIPMENT RESTORATION ACTIONS

Our current efforts are in the development of a real-time computer network and data storage system. This will, as a part of its function, measure the non-availability of service as a "criticality" of incident ranking, as evaluated by our Central Control trouble staff.

Our personnel will be instructed to consider many factors in this evaluation. Among these will be the absolute delay of the train, the percentage of the system secondarily affected, the time relations to peak-commuter-hour service, and the general performance of the system at that time, exclusive of the particular incident being reported.

Of all these and other various possible measures of performance, the rate of cars failed in revenue has the advantage of being the most unbiased estimator of vehicle equipment performance and as a primary element in the total maintenance load factor. It has the disadvantage of being the least sensitive to the feelings of our patrons.

At the present time the number of serious system delays and the more sophisticated version now being planned have the advantage of being closest to the passenger. In addition to the subjective factors mentioned, these evaluations show that the single most frequent cause of delay is not particularly equipment- or system-oriented; it is the human factor, both from actions or omissions by patrons and employees. Amounting to about 20 to 30 percent per month, it should receive considerable study from operations personnel, but it must be screened for evaluation of systems and equipment maintenance data. An evaluation of the various current performance indices utilized at BART is given in Figure 5.

From the observations about the subjective nature of passenger delay statistics, it is evident that such evaluation measures are possible. During the next year BART will attempt to implement one such measure known as the Tape Merge Project. This will provide a computerized merging of the information within our

INDEX	Relation to Incidence of Failure	Relation to Hardware Reliability
DELAY EVENTS	Subjective Selected Subset but does pick up non-vehicle causes	Very little - Hard to establish trends patterns
UNSCHEDULED TRAIN REMOVAL	Subjective selected subset - Only Vehicle Related	Possible to relate to System & Equipment causes still somewhat subjective
CAR REMOVAL	Removed from all Vehicle events only by the possibility of multiple revenue events on the same car.	Considered a good Indices of Vehicle Systems Performance
ALL REVENUE EQUIP. INCIDENTS	Omits only Non-Revenue Incidents - Otherwise this is the incidence of failure.	Best source of Revenue Equipment Evaluation.
HARDWARE MAINTENANCE DATA	Does include non-Revenue Failed Hardware - Omits system failures for which no hardware source is identified.	Does show secondary failed hardware - Otherwise this data defines Equipment (but not System) Reliability.

FIGURE 5. EVALUATION OF PERFORMANCE INDICES USED AT BART

electronic fare gate data and the central computer data on train station departure delay. This work is based on the efforts of Welker, et al, of TRW, as a part of their Government-funded studies of BART system availability and safety.

From a maintenance perspective, however, the proposal suffers from an extremely severe deficiency. No effort is being made to link the passenger-minutes of delay thus evaluated in relation to the causal incidents at their source.

One needs to know the answers for situations in which performance indices indicate a change in trend. One must also be able to identify operational factors, system unreliability, and equipment unreliability by methods other than a best estimate of data obtained through manual analysis.

On a large system such as BART the necessary data will be most economically collected, stored, and analyzed by the computer, in our opinion. Operational needs for certain elements of information in a real-time output make it economical for us to collect our failure data in the same mode. However RM&A (Reliability, Maintainability, and Availability) measures, only, would be more economically collected by a batch-input process.

At this point several different systems have been developed specifically for Rail Transit System R&M (Reliability and Maintainability) data collection. New users should carefully look at already developed systems, because the overall development of software for just the basic R&M data alone will require 2000 to 4000 hours of programming and engineering time.

It is extremely important to ensure that the general data criteria and retrieval capability of the software are monitored by experienced RM&A personnel. It is difficult to define that point at which simple manual data storage and retrieval would suffice. We estimate that when the number of incidents to be recorded exceeds 100-200 per month, manual storage and retrieval systems can no longer be efficient.

Copies of our new Incident Reporting Forms for vehicle and non-vehicle incidents and the supporting Component Repair Detail Form are shown in Figures 6, 7, and 8. This will provide some familiarity with the data to be collected and provide some basis for consideration of data problems.

We have established a Reliability Engineering organization at BART whose primary function includes the collection, storage management, and analysis of our System and Equipment R&M data. The output from this organization provides status and trend data to our management, and evaluates changes which occur due to modifications.

The greatest problem in any such data system is the process which precedes the computer. The software is a complex but "clean" problem. The understanding and, in some cases, the willingness of the personnel providing the basic input to be accurate, logical and, most important, consistent are, in our opinion, at the heart of the data problem.

A position has been established within BART's Reliability Engineering group whose sole responsibility is to review the daily inputs to the new data base and to take steps to provide an acceptable level of accuracy.

Some of the data currently collected and analyzed was shown in Figures 1, 2, 3, and 4. Not much is currently collected or known about our service availability in a statistical sense, but there is on hand much data on equipment reliability, maintainability, and availability. BART has been, from an equipment standpoint, probably the most analyzed rail transit property in the world. Data on BART vehicle equipment availability is shown in Figures 9 and 10.

I feel that there is nothing difficult about the data process on a technical level. Other complex-system industries have preceded us and solved this problem. The real questions are more likely the following:



VEHICLE INCIDENT REPORT INCIDENT CIRCUMSTANCES AND FAILURE DESCRIPTION

INCIDENT NUMBER
A000067

INCIDENT SECTION

TAG NO. MOD NO. DOCUMENT NO. OF DOCS INCIDENT DATE CAR NO.

24 HOUR CLOCK
INCIDENT TIME SYMP. CODE DIRECTION SPEED MOOE LOCATION WEATHER

YARD OR CONSIST OASH CARS IN CDNSIST

DISCOVERED DURING 1. REVENUE SERVICE 2. UNSCHED REPAIR 3. SCHEDULED PM 4. YARD MOVE
5. TESTING 6. OTHER (Explain) _____

INCIDENT NARRATIVE _____

PREPARED BY _____

FAILURE DIAGNOSIS AND REPAIR SECTION

EQUIPMENT CODE STYLE NUMBER SERIAL NO. OFF SUB

GROUP SYS SUBSYS _____

1. PRIMARY 2. SECONDARY ODOMETER MILEAGE SERIAL NO. ON SUB

REPAIR NARRATIVE _____

NOTE: IF MODIFIED COMPONENT USED ALPHA CODE
1. (A) NO TROUBLE FOUND 6. (F) SCRAPPED
2. (B) REPAIR 7. (G) OTHER (Explain) _____
3. (C) SENT TO COMP. REPAIR SHOP
(NOTE: HARD COPY OF REPORT MUST ACCOMPANY DISCREPANT ITEM)
4. (D) ADJUSTED 9. (I) NO PART AVAILABLE
5. (E) RESET

REPAIR DATE EMP CODE LABOR HRS ELAPSED HRS. MAINT. FOREWORKER _____ Q.I.

FAILURE DIAGNOSIS AND REPAIR SECTION - CONTINUED

NO.	CDMP.	TYPE	COMPONENT DETAIL	SERIAL NO.	STOCK NO.	FAULT CODE	DISP. CODE
<input type="text"/>							
<input type="text"/>							
<input type="text"/>							
<input type="text"/>							

FAILURE COMPONENT CHARGABILITY TO OTHER WARRANTY CRITICALLY

Form No. 0918 (7/76)

FIGURE 6. INCIDENT REPORTING FORM - INCIDENT CIRCUMSTANCES AND FAILURE DESCRIPTION

SYSTEM & EQUIPMENT INCIDENT REPORT

INCIDENT NO. **N000059**

NO OF DOCS DISCOVERED DURING WEATHER

SYMP. CODE REGISTER READING

INCIDENT DATE INCIDENT TIME

EQUIP NO. CODE ITEM LOCATION

LOCATION

INCIDENT NARRATIVE

ITEM NO. STYLE NUMBER

1. PRIMARY 2. SECONDARY

REPAIR NARRATIVE

3. SENT TO COMP. REPAIR SHOP (NOTE: HARD COPY OF REPORT MUST ACCOMPANY DISCIDENT ITEM)

4. ADJUSTED 5. RESULT 6. SCRAPPED 7. OTHER (EXPLAIN)

8. REPAIRED 9. NO PART AVAILABLE

REPAIR DATE EMP. CODE EMPLOYEE SIGNATURE LABOR HRS ELAPSED HRS TIME OF REPAIR

Form No. 0917 (7/76)

INCIDENT REPORT

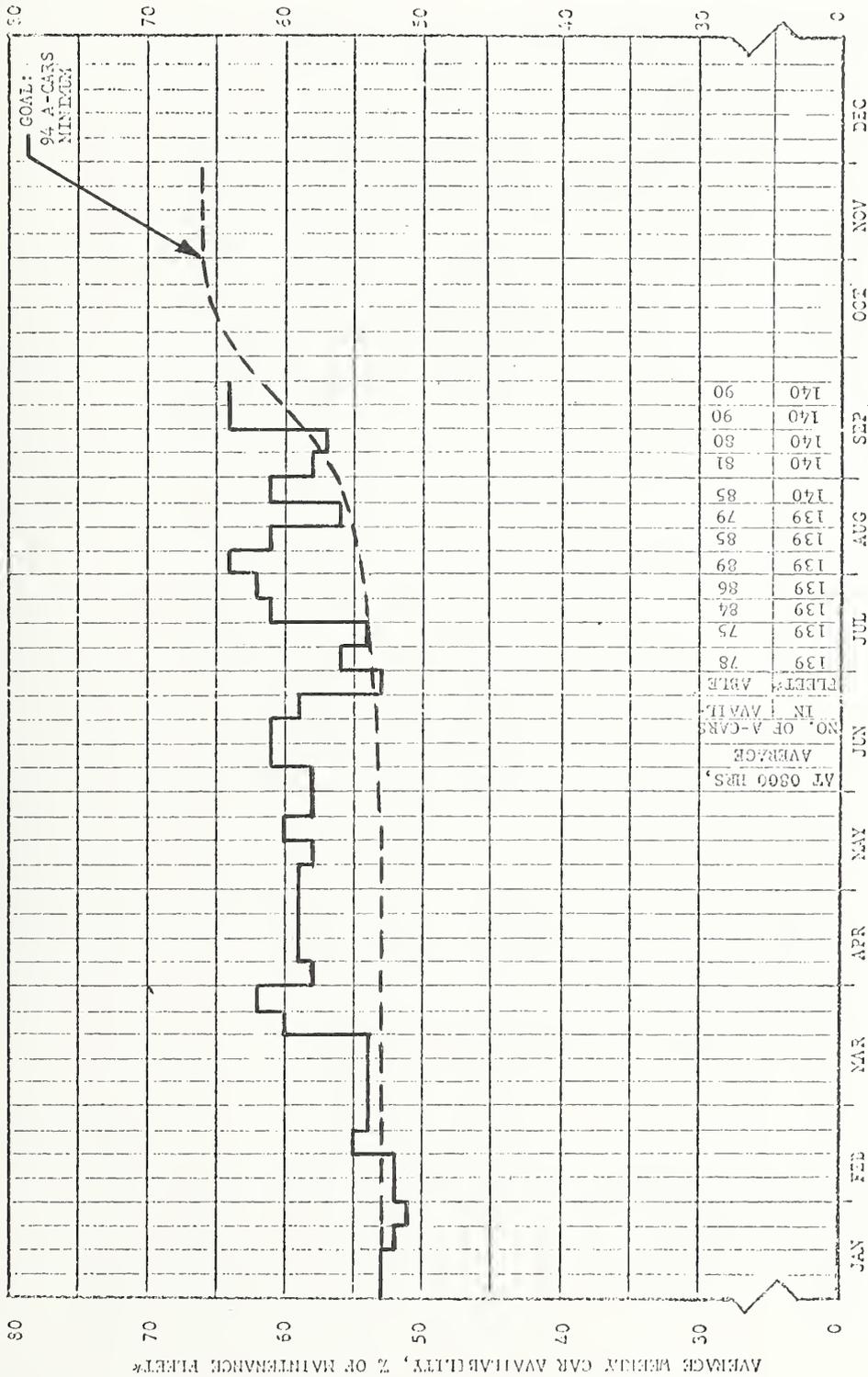
NO.	COMP.	TYPE	COMPONENT DETAIL	SERIAL NO.	STOCK NO.	FAULT CODE
<input type="text"/>						
<input type="text"/>						
<input type="text"/>						

FAILURE ASSESSMENT: CHARGEABILITY TO MTBI REL. WARRANTY CRITICALITY

ADDITIONAL INCIDENT NARRATIVE

CORRECTIVE ACTION FOR FAILURE OR ACTION TO PRECLUDE RECCURENCE

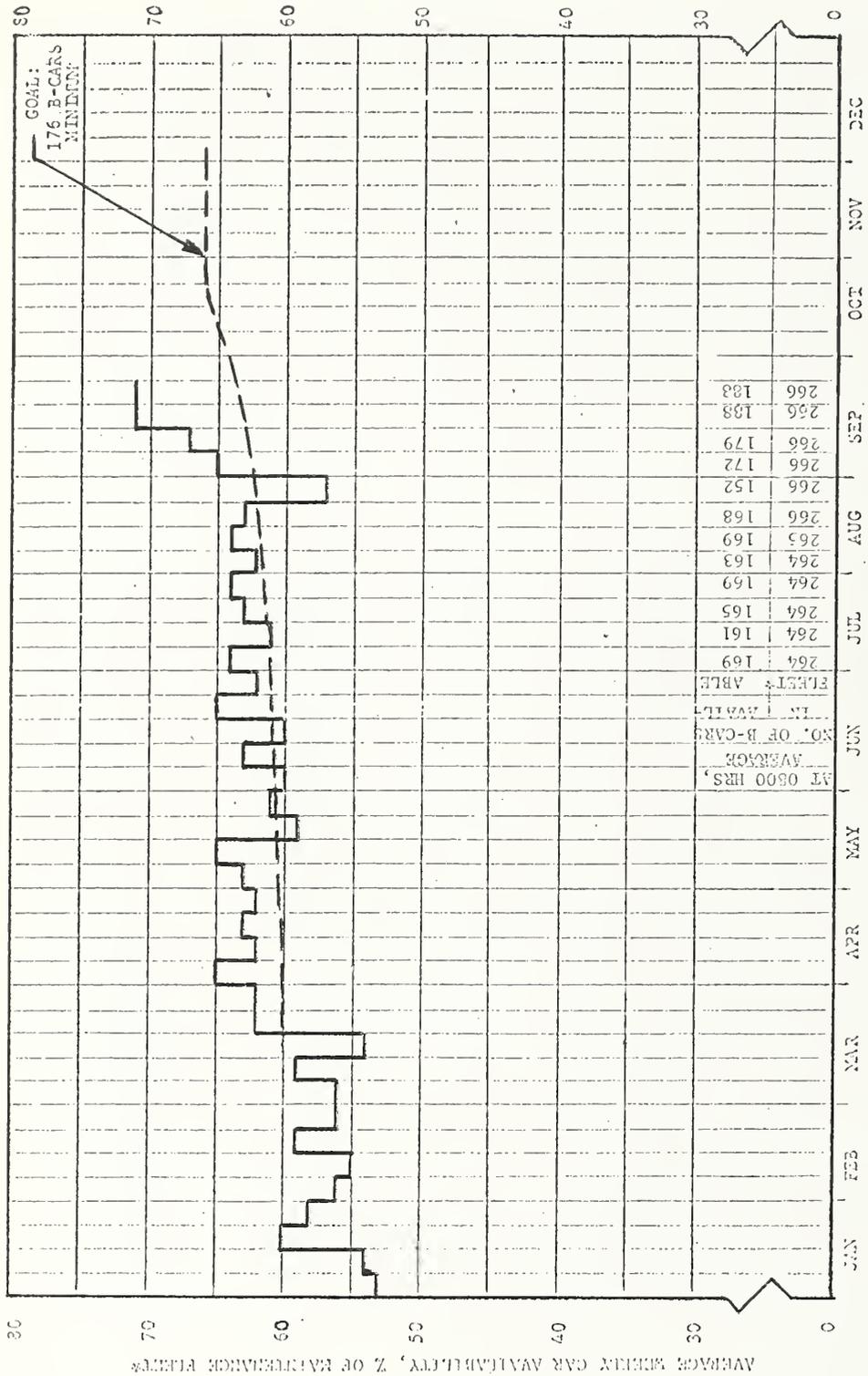
FIGURE 7. INCIDENT REPORTING FORM - SYSTEM AND EQUIPMENT INCIDENT REPORT



Source: Weekly Summary Car Report
 * Maintenance Fleet = All Cars less Long Term Out-of-Service Cars

FIGURE 9. WEEKLY A-CAR AVAILABILITY, 1976

RELIABILITY ENGINEERING



Source: Weekly Summary Car Report
 * Maintenance Fleet = All Cars less Long Term Out-of-Service Cars
 RELIABILITY ENGINEERING

FIGURE 10. WEEKLY B-CAR AVAILABILITY, 1976

1. Given that a property is satisfied with their performance, do the resources exist for providing the necessary management actions to ensure the desired level of data?
2. Does the industry realize the concepts of systems engineering and system assurance disciplines sufficiently to hire and to train, in these disciplines, significant numbers to make a difference?
3. Is the public willing to pay for the added costs that are needed to bring our systems assurance programs into better balance with the systems performance demands?

A number of years ago, at the annual reliability and maintainability symposium, a keynote speaker made a point which has had a lasting impression on me. In effect, he said:

"You people come each year and hold your meetings and congratulate yourselves on how much you have learned. At the same time, the equipment which I get to use in the field gets less and less reliable each year. The problem is that you folks have been talking to each other. You people have some good ideas, but you don't know how to sell them to your top management and your fellow workers outside your discipline. Until you learn how to do that you might as well recognize you're just talking to yourselves."

In short, I believe that there is no lack of knowledge on AGT service availability or how to measure it, report it, analyze it, or specify it. I think what we need to know is how to sell it.

(End of Paper 3 Presentation)

Mr. Vigrass

Thank you, Jim. I think what you told us is very pertinent to what the meeting is all about. Are there any questions?

Mr. Pawlak (TSC)

Three questions for Max Bitts. First you mentioned one person per vehicle. Then I heard that you operate your system

20 hours a day and seven days a week. I understand that there are 12 people involved in the overall effort, and not per shift.

Mr. Bitts

That's right. At the end of the month we have expended 12-man-months of effort on all the vehicles.

Mr. Pawlak

Does that include the wayside as well as the cars?

Mr. Bitts

Yes. However, it does not include the computer operator who provides safety, security, and TV functions.

Mr. Pawlak

His work is only a part-time operation, anyway.

Mr. Bitts

Twenty-five percent of the time.

Mr. Pawlak

Is he the only one doing such work?

Mr. Bitts

Well, there are two men involved, but actually, one man assigned twenty-five percent of the time is all we need. We operate 24 hours a day, with three shifts of two men per shift, and 21 shifts for the entire week. At each shift two men are present in the Central area. One of these two men is available to us for twenty-five percent of the time during which we run cars. We can vary the operations, such as transfer of cars, putting a car in, or taking one out, or skipping stations. But at any rate, when you add up the operations, the manpower effort amounts to a man per car.

Mr. Pawlak

The other question relates to service interruption. I know you have three stations on a loop, and that if you have a problem at a station, as a worst case you can always push the vehicle between stations and then run a shuttle. Now would that be classified as a service interruption?

Mr. Bitts

If we establish the shuttle and maintain it for approximately two-minute spacing per station, we wouldn't call it a service interruption. But normally, by the time we establish a shuttle, we probably have had a bit of measurable failure.

Mr. Pawlak

Assuming that the mean time to restore is fairly low, and that in a number of cases part of the restoration time includes running time, can you give me an idea of how long it actually takes a man on call to get out to the vehicle? And how does the time to get him out there compare to the time it takes to restore the system?

Mr. Bitts

I'd say that in 90 percent of the cases it's a matter of his getting there, boarding the vehicle, doing something like re-cycling a door, riding around the next station, and getting back to his home area. Actually, we had a logistics problem getting people to the car.

Question from the Audience

Max, what is the average running time of each vehicle per week?

Mr. Bitts

Well, it's about 4,000 miles a month. They run for 20 hours a day, with six cars running as a minimum all the time. It's sort of interesting that the average running time per bus is about 2-1/2 man-hours. It would be interesting to take data from this as criterion and put it in those terms.

Incidentally, according to one of my men, he had six to seven failures per thousand hours of operation actually almost six per thousand car-hours of operation. With a minimum of six cars running and an approximate total of 45 failures per month, then the total running time for the six cars is about 7400 car-hours per month. This figure is based on 20-hour-per-day operation, 31 days, and 12 cars used at a minimum of six at a time.

I wish to inform you that I have a couple of copies of our monthly reliability report that actually lists every failure and identifies it as patterned, or intermittent, etc. If anybody's interested in our system, I'd be glad to make these copies available.

Mr. Watt (TSC)

Jim King. Am I right in assuming that in Figures 9 and 10 in your paper the percentage of the BART fleet available for a particular week is related to the numerical data indicated for that week?

Mr. King (BART)

Yes, it's the percentage of the maintenance fleet, which is defined as the total number of revenue vehicles we have minus the number of cars which are out of action for long-term periods.

Mr. Watt

Well, for example, referring to the first week of July, with 139 A cars in the fleet and 78 available, does that mean that 139 minus 78 were out of service because of failure, or just not needed that week?

Mr. King

It might have been because of failure, or because a part was not available, or because modifications were being performed on them, or for any number of reasons.

Mr. Watt

So the effective fleet consisted of 78 cars.

Mr. King

I'll give you my personal feeling. BART has asked me to retain this index. I feel that a proper index ought to be based on the number of cars that we propose to use for revenue service on a particular day, and availability ought to be gauged against that index. I've been asked to hold to the present index, which indicates, for this particular five-day week, an availability on the average of 78 cars at 8:00 a.m. If you look at it at 4:00 a.m. or 12:00 noon, it's going to be a different number.

Mr. Frank Smith

I think you've touched on something very interesting. Why not keep a couple, or even three indices? I think this one is a measure of interest to certain mechanical folks. Your index of the number of cars available versus number scheduled is another index. I don't see why you can't keep them both.

Mr. King

I think that ultimately, to satisfy all the various interests, we're going to have to look at passenger dependability-availability, system availability, and equipment availability, and divide the data different ways. I'll start at the number of events. Currently, we do not monitor an event if one train does not stop at a station, but the situation doesn't repeat. That occurrence is normally called an event. If the events are significant in some way because of severity or repetition, you then have what I call an incident. And the incident may or may not generate a passenger disruptive delay. It may or may not generate a removal from service. And I think we're going to have to go on computer and put all of these numbers in, so that we can really service all the various people who want to know. It's a tough problem, and it does cost money.

In terms of incidents, about 85 percent of our incidents occur on vehicles, and 15 percent on non-vehicle areas. Also, about 10 percent of the significant incidents have to do with the wayside ATO (Automatic Train Operation), particularly that subgroup that's known as the multiplex system. It's a very complex thing. But then, if you look at it in terms of passenger delay, in terms of how it affects the system availability, you get a bunch of different answers.

Mr. Pawlak

The other aspect relates to the question of taking a vehicle out of service, and then not being able to specify exactly what it was that caused its removal. What percentage of the cars taken out of service, would you say, end up in that category of cars going back on the line without the original problem having been solved?

Mr. King

I would say that of all our incidents we have been 25 and 30 percent that we like to refer to as "no trouble found." I'm trying to get people to call it "trouble not identified."

(End of discussion on Paper 3)

Mr. Vigrass

The fourth speaker today will be Ken Bissett, Superintendent of Signals and Communications with Chicago Transit Authority. Ken obtained a BS Degree in Electrical Engineering from Illinois Institute of Technology in 1971. During the time he was studying, he was a co-op student with the Milwaukee Railroad for part of that time, and for another part with the Chicago Transit Authority. So, when he began working there as an Electrical Engineer, he already had about four years of experience. Ken does the engineering part for the Signals and Communication Equipment for CTA. They have a cab signal system for train separation. And he will tell us about CTA measures and the data they accumulate and use for the subject of reliability.

PANEL 2
PAPER 4

CHICAGO TRANSIT AUTHORITY
SYSTEM RELIABILITY
CONSIDERATIONS

K. BISSET

CHICAGO TRANSIT AUTHORITY SYSTEM RELIABILITY CONSIDERATIONS
K. BISSET

I will start this discussion with a brief description of our property. We have both rapid rail and bus systems, but I'm going to confine my remarks to the rapid rail system. We have approximately 200 revenue track miles, and approximately 1,100 rapid transit cars. They are about 50 feet long, with about 45 seats in each. Generally, they are in pairs, although we have about 50 single cars as well. We run trains up to eight cars long, with two-man crews except for certain lines. The Skokie Swift line is a five-mile line, with two stations on it; it runs with one-man crews. The Evanston line is a five-mile line, which runs with one-man crews in the off peak.

We carry approximately 600,000 riders per day, and we provide service 24-hours per day and seven days per week on most lines. We have minimal automation. Departure from terminals is controlled by automatic dispatching clocks, with extensive manual override available. The supervision is quite primitive. We have a number of pen recorders which record the passing of trains at certain locations up and down the railroad. Therefore, the supervisors only note exactly where a train is at certain particular locations. Our train operation is most exclusively manual; the only automatic features are a cab signal system and block signal system. We have over-speed protection on the cab signals and trip stops in force at way-side signals in those areas that are so equipped.

The measurements we make on our system availability are based on the line log, which is a fairly extensive document. A typical example contains 10 pages and covers 24 hours. It includes all of the events occurring on the rapid transit that the line supervisors become aware of. It includes such information as the delay, a brief description of what the trouble is, and what action was taken to correct it.

There is also the mini-log, which is a summary of those items which caused a greater-than-10-minute delay. This goes daily to the General Manager's office. Also, if there is any delay greater

than approximately 20 minutes, the General Manager is notified by telephone. If it's greater than 30 minutes, he's notified by telephone even if he is not in the office. We have a sort of club over our heads to keep the system operating well, so that the General Manager won't have a whole lot of things presented to him as problems.

As for the advantages of this system, it is, first of all, quite cheap. It is flexible; that is, it handles new systems, new cars (for instance, we added the cab signal equipment to the existing cars), or new operating procedures. We also get a fairly detailed description of a failure occurrence, so that we can track down the trouble.

There are disadvantages, of course. There are no numbers whereby I can give you graphs to show how well we're doing with our maintenance. It's also a bit difficult to get trends out of this data, though it is possible. If we're interested in the trends on doors, for example, we go back a few months and count a couple of days' line logs and find out how many door problems we had; then we count them again today, and so we have an idea of what sort of trend we are having with door problems. We mainly depend on the maintainers' "feel" for the system. Basically, there are no numbers for management to look at to see the sort of problems we're having.

Since we have no real measures and no real relationship between our delay measures and the hardware, the delays that are reported are not just hardware problems, and so are not really a very good measure of hardware reliability. But it's pretty apparent, from the description, when a hardware problem does actually exist.

We have a number of techniques for minimizing the delay to passengers. Some of them are pretty straightforward (e.g., the express trains pass stations). We also can, in certain instances, reroute trains. Downtown we have a double-track loop system which has three lines converging into it; trains come in

and, in a couple of instances, run around the loop entirely and return on their original path. One other line runs through the loop, around two sides of it. So, a certain amount of rerouting is possible.

Other techniques are available also to minimize any possible delays. We don't have a real management system for failures. Questions are presented on our question sheet as to whether a passenger delay measure of service availability is possible or feasible. With our system it would be quite difficult, because we do not monitor, as BART does, the passenger flow through the system. We have some idea of the number of passengers entering at a station. In general, however, we don't know in which direction they're going, nor do we have any plot as to when they entered, or how many entered during any period. So, on our property it would be quite difficult to do the kind of analyses that David was talking about this morning.

Let me point out that we do have a certain amount of data collection for failure analysis. This has been almost exclusively confined to the signal system. Some people are concerned about the new cab signal system feature on our property; in spite of this concern we have had some success with an analysis of the failures of the carborne cab signal equipment. These analyses have been pretty much directed to the newer systems. (We have had some equipment in service since 1967, but we have done no analysis at all of that equipment. From past experience, we have a basic confidence that it operates very well.) These analyses are carried out as time permits; when we see that we may be having a problem, we start analyzing it in a little more detail. Again, it's a matter of referring to the maintainer, who has a pretty good grasp of the situation, and then we try to quantify it. We are bringing on line now a system for analyzing failures on buses-- we call it BUS, Bus Utilization System; this is a real-time system with terminals in the line office, where troubles will be reported by the bus operators. There are also terminals in the garages, so that the bus mechanics can report what action was taken on a specific report of trouble. That's very slowly coming on line

now, and there are plans to extend it to the rail system after the bus system is working well. That looks like it's going to take quite some time.

I have a few general comments on daily measurement problems. There will undoubtedly be some problems with any sort of measurements that you are going to make on system availability. Taking one day's time log as an example, I looked through the log and noticed a logging of a 15-minute delay due to a disturbance on a train. Although fire department and police department personnel were sent to the scene, no complaint was signed, and no action was taken on it; however, it did cause a 15-minute delay to the system, even though no hardware failed.

There are still other instances of non-hardware-caused delays. We had a sick rider on a train. Ministering to him caused a 14-minute delay to this train, 13-1/2 to his follower, 11-1/2 to the follower behind that one, and 10-1/2 minutes to the fourth train down the line. This sort of "failure" should be accounted for in such system availability measures, even though it may not relate to hardware at all.

As noted in the second example, a given delay can create problems of a cumulative nature. The first train was delayed by the sick passenger for 12 minutes. Service restoration techniques were initiated, that is, the train was run express past several stations; but even so, the station platform loading of people was enough to have built up an additional two-minute delay even though service restoration techniques were instigated. This is a serious problem; we are very careful with our service restoration techniques to try and minimize the additional delay. It can get to be very serious especially with the type of equipment that we have. For example, doors are not particularly wide. There are blinker-type doors on all of the equipment that we've gotten up to the present time. Passenger flow out of and into the cars is not as free as might be available, as, for instance, in Toronto, where they have very wide aiseways and very wide doors, and where cars can be emptied quickly.

Also, another problem with delays relates to the performance of routine maintenance. We operate 24 hours a day; therefore, maintenance has to be carried out on a wayside under traffic. Such maintenance is bound to cause some problems with service. Right now we are undergoing a track renewal project on the Northside. Luckily, in this area we have four tracks, so we can reroute trains somewhat. But there is a problem. The station platforms are accessible to the center two tracks only; the two outside tracks are strictly express. So, we have to put in temporary platform extensions at certain locations; some passengers have to backride; the trains have to slow down while they cross over from one track to another. This sort of thing causes delays, again not hardware-related.

I have not offered figures or graphs or measurements in this discussion. The fact is that when you get onto a fair-sized rapid transit system, I find that there are a number of problems which are rather difficult to quantify, and that care should be taken if you are going to do so.

(End of Paper 4 Presentation)

Mr. Vigrass

Thank you, Ken. Any questions?

Question from Audience

How many times a month do you have to call the boss at night? Sounds like you've got a pretty good indication system of your performance there.

Mr. Bisset

Yes. I wouldn't like to count up the number of times a month. The number of times I would guess would average out to be something like once or twice a night. I might point out that this 15-minute delay that we had due to the disturbance on the train may have been called in.

Mr. Sadowsky (California PUC)

I think your statements concerning the real-life problems in the system were a very valuable contribution in terms of how you should really look at system availability, and how non-equipment-

related problems may influence the reliability index or reliability numbers. I was impressed also with the concluding quote that Jim King had in his statement. I was just wondering if we are talking to the right people, or if, perhaps, we should have a broader type participation, with operational-type people rather than just with people interested in what I would consider the system- and assurance- and ability-type of activities. I think it would be worthwhile considering that for the next conference.

Mr. Vigrass

That's a good point. And I think that once this technical group has its definitions agreed upon, it might be a very good thing to get in with people from APTA's technical T&O, Transportation and Operations. Anyway, it might be a very good thing to coordinate the whole thing with the operating side of APTA and the chief operating officers of each property once the definitions are agreed upon.

Mr. Pawlak

I wonder, Ken, if you could briefly state the sequence of events surrounding that January accident in the sense of conditions or the criteria for dispatch of a train, and how that impacts on availability. I'm aware that before the accident there were certain ground rules for dispatching a train, and that as a result of the accident, those rules were changed, and that there was an impact on the service as you improved things to get back to normalcy.

Mr. Bisset

Well, the accident Mr. Pawlak was referring to was the tail-end collision at the Addison Street Station on the Kennedy line. The following motorman was operating on the bypass of the ATC (Automatic Train Control) equipment; thus, we had no signal protection. Our prime goal, and this is not explicitly stated anywhere that I've seen, but everybody knows it on the CTA, is to provide the best service that we possibly can to our public. We want to minimize their delays wherever possible, and minimize

their inconvenience. As such, in this particular instance we had a train that was delayed coming out of the yard. The cab signal equipment on the car was reported in bad order. The decision was made, rather than inconvenience passengers and delay them an additional 10-15 minutes. The object was to get the people downtown, so the train was put out on line, unfortunately. At that time, immediately following the accident, the operations were changed so that a train with defective cab signals could not be put out on the road; and should cab signals fail while out on the road, the train had to be unloaded and brought back to the nearest terminal, and taken out of service. I'm not sure of the numbers but the first month that we had that operation in service, they were enormous. We had a large number of trains unloaded. By the way, I might say this is an additional measure of service, if you will. It was in the neighborhood, I think, of 50 or thereabouts. On the minilog that is sent to the General Manager, the number of trains unloaded due to cab signal problems is noted.

We're now down to zero; we haven't had one for quite a while. This is due in part to improved maintenance on the cab signal equipment, and in part to slightly modified operating standards as to what really is a bad order cab signal. On occasion you get reports of light bulbs burned out in the ADU (Aspect Display Unit). This doesn't affect train safety; it inconveniences the operator a bit because he doesn't really know how fast the train is supposed to go. But if he accelerates the train, when he gets an audible alarm he knows he's going too fast and that he should slow down. So, it's not a safety factor, but it is inconvenient, and it is not the sort of thing one would unload the train for. This sort of problem was recognized, and the operations have been changed somewhat to allow certain types of failures which don't affect the safety of the train to allow it to remain on the road.

Question from Audience

Is your preventive maintenance program increased?

Mr. Bisset

Well, we started to increase it, yes. Part of the problem, of course, is that the equipment is rather more sophisticated than standard signal systems. We don't just go out and ask for five maintainers for this equipment, and immediately put them on the job. We have to train them for quite a while. So we are not improving our preventive maintenance. That is, whenever a train comes in for its 6,000-mile checkup, cab signal equipment will be completely checked out also. But manpower to do this is slow coming aboard.

Question

I guess my question really is, are you solving this problem by better diagnostics or something associated with unscheduled maintenance, or is it because you're now introducing maintenance programs?

Mr. Bisset

I think it's mostly because of the better diagnostics on the unscheduled maintenance. We did install, by the way, a departure test at Jefferson Park, and to date it hasn't found a single case of bad order.

Mr. Vigrass

The Chicago cars, at least the older ones, are pretty basic; they're not air-conditioned and they have no automation. The later models are more complicated.

Mr. Bisset

The original equipment, the older equipment that we have in service, now constitutes the bulk of our 1,100 cars, and is converted from PCC street cars. It uses essentially the same trucks, very similar control gear, and so on.

On the question of automation, we decided that we needed a study of the possibility, on the next order of our cars, of going to a higher level of automation. We decided, after talking with people at PATCO and several other properties, that we really

didn't want to do this. One of the things that has come out of our installation of cab signals is that we know that motormen tend to rely quite heavily on the cab signal system, to the point where they don't pay as much attention to the track ahead as perhaps they ought. And you will find this problem to be corroborated if you talk to the track maintenance and signal maintenance people for the wayside and ask them how many close calls they've had with trains bearing down on them and motormen not being aware that the men were there on the track. That's an example of the sort of problem that you can run into with increased automation. Obviously, if we were to go to a fully automatic system with nobody aboard the train, no man would go out on the track; but then we have the problems of how to provide maintenance. Where do you fix this wayside equipment? This was a consideration that we looked into, one of the considerations that led us to not go to a higher level of automation.

(End of discussion on Paper 4)

Mr Vigrass, PATCO

Now, I will offer a few remarks as to the fifth and last speaker. I have a paper up front here, and I have a few copies left if anyone cares to look at it. To review, I'm Bill Vigrass, Superintendent of Equipment at Port Authority Transit Corporation, New Jersey, the operator of Lindenwold High-Speed Line, which prides itself as being the very first semi-automated rapid transit line to give regular service. It has been in service since January 4, 1969, and, since March 22, 1969 has been under automatic operation; the first several months were run manually. It's 14-1/2 miles long, with 12 stations, providing 42,000 one-way rides per day. There are 75 cars - 25 single-unit cars, and 25 joined pairs, comprising 50 cars, for a total figure of 75. There are 70 people in the car equipment department to maintain the cars, including cleaners. We run 24 hours a day, 7 days a week. During midnight hours there's one train out running every hour from midnight to 5:a.m., and this runs in concurrence with wayside maintenance. The track department can take over one track, and

the solitary train can shuttle back and forth on the other. Train lengths are 1, 2, 3, 4 and 6 cars on schedule; occasionally, we run a five-car train if we're simply short.

Now, to respond to the specific questions in the TSC outline, I addressed these as specifically as I could, given the fact that some of them I couldn't respond to at all.

PANEL 2

PAPER 5

ANSWERS TO QUESTIONS POSED BY THE
TRANSPORTATION SYSTEMS CENTER

J. W. VIGRASS

ANSWERS TO QUESTIONS POSED BY THE TRANSPORTATION
SYSTEMS CENTER

J. W. VIGRASS

1. How do present operators of rapid transit systems evaluate and characterize their systems?

PATCO regularly evaluates its on-time performance. This is done manually from data logged on the dispatcher's daily Unusual Occurrences (U.O.) Report. Each day every delay in excess of four minutes is logged, every annulled train is noted, and any time a station is by-passed to allow a delayed train to regain its schedule is recorded. Since there are ten intermediate stations between PATCO's terminals, ten missed stations are calculated as one annulled train. The sum of (1) late trains, (2) annulled trains and (3) by-passed stations divided by ten is logged on each day's report. PATCO schedules 338 weekday trains (one way trips), 302 on Saturdays and 160 on Sundays and most major holidays.

2. What measure is used?

The percentage of trips run on time is calculated for each four-week accounting period. There are 13 such periods per year.

PATCO has achieved an average of 98.17% trips run on time in 1976, similar to prior years. In severe winter weather, this has dropped to 97%, and in fair, dry months (often September and October), 99% has been achieved. While 100% has been achieved on selected days, the longest such period was seven consecutive days, with 1855 trips being run "on time". Such occasions are rare!

While PATCO's record is very good - we like to think it is the very best - its experience is that about 2% of its trips are adversely affected by various events. This results in an

average of about six delayed trips per week-day. Usually, these delay only one train's passengers, and for a period of less than ten or eleven minutes.

Causes of delay can be grouped into three categories: (1) car equipment malfunction, (2) wayside (signals, power track, etc.) or (3) "outside" events, such as overcrowding, fire in buildings alongside the right of way, or passenger emergency (illness or injury). Most of these are dealt with promptly by the train operator on board, roving supervisors, or wayside maintainers. Car equipment is not repaired on the line, but is moved to the shop under its own power, if possible, or by pushing by the following train if necessary. Without a person on board, the result of such malfunctions would be far more serious. In my opinion, major stoppages would occur rather than minor delays.

3. What are their advantages and disadvantages?

The on-time average is a gross overall average, and does not pinpoint causes or assign responsibility. Each department head gets a copy of the daily U.O. report, reads it, and determines what his department did to respond to a delay. With the small PATCO system, this personal approach works. Recurring problems are usually evident quickly, and corrective action is taken. In an overall sense, the result is that most events in the U.O. are random, after selected recurring items are screened out.

For a larger, more complex system, a more formal analysis of causes of delays would be desired.

4. How do these measures relate to hardware reliability and incidence of failure?

In a word, they don't! Reason for delay is entered on the U.O. report manually, and only for internal department uses. However, within the Equipment Department, there are several reports generated by PATCO's own modest computer center on its IBM 1130, a small machine using FORTRAN, a scientific computer language.

Every maintenance activity is entered on a "defect report" showing the car number, date, symptom of defect, repairs made, by whom, man-hours consumed, and material or parts used. These are keypunched and then tabulated on several printouts. Two printouts present an accounting period's (4 weeks) activity by (1) car number and (2) major subsystems.

Another printout tabulates by car number, listing miles traveled that period, number of unscheduled maintenance occurrences, man-hours expended thereon, mean operating hours between failures (i.e., unscheduled maintenance events, not necessarily a "failure" that causes a delay or unscheduled removal of a car from service), and number of man-hours to repair each occurrence. This is subtotaled by car type and by total fleet. A typical 4-week period showed five occurrences per single unit car and eight per joined pair, roughly one event per week per car in addition to scheduled preventive maintenance.

Another printout tabulates major subsystems across the fleet by number of events, man-hours expended, percent of man-hours per subsystem, and system totals. Preventive maintenance (inspections and cleaning) is included as though it were a subsystem to illustrate the relative expenditure of man-hours on scheduled versus non-scheduled maintenance. Scheduled activity has risen from about 30% to about 40% in the past three years as a result of positive efforts to improve reliability. MTBF for subsystem or components is not yet calculated, but this is an objective for 1977-78.

5. How effective are failure management systems in reducing passenger delays?

Manual analysis of PATCO's reports is the present means of interpreting them. In the small PATCO system this approach has been relatively effective. This has been primarily to identify components requiring modification or replacement by a redesigned part or subsystem. In some cases a need has been evident, but no solution has been attained.

The addition of MTBF data would allow scheduled replacement of problem-causing components prior to their failure. An objective of routine replacement at 80-85% of average life would reduce failures in service to a very low number.

6. Is a passenger delay measure of service availability possible? Would it be feasible?

Nearly anything is possible, if one disregards cost. In a system having automatic fare collection (AFC) with both entry and exit controlled, such as PATCO, it is possible (but not done) to continuously calculate the number of passengers in the system via data links to a central computer. With origin and destination checked by AFC and with a central clock, it is entirely possible to calculate passenger delays. A better question would be, "Why do it?".

Whether it would be economically feasible is a good question, one tending to a subjective assessment by the system in question. It would be an interesting statistic, but would it really be useful?

No attempt has been made by PATCO to calculate such a number, because the number of persons affected is tremendously influenced by (1) the location of the event, (2) the time of event, and (3) other circumstances. A certain defect may affect no one if it occurs to (a) a train at Lindenwold terminal at a time that allows a different train to replace it before scheduled departure. On the other hand, the same defect occurring to (b) a train in the Philadelphia subway toward the beginning of the evening rush hour would adversely affect several thousand passengers. Our present system simply reports both events. If a system would weigh the impact, it would give (a) no weight, and so do nothing to prevent (b). That wouldn't be too smart.

7. Is anybody using one, i.e., a passenger delay measure?

No, not to my knowledge.

8. How can the necessary data for any measure be economically defined and analyzed?

See No. 6 above. An AFC system tied to a central computer could do it. Each trip, by origin and destination, would have a maximum travel time. Any passenger exceeding this time would be a statistic to be recorded.

9. Data problems: review and discuss.

See all above items.

10. What data are now being collected for reliability and maintainability purposes?

See all above items.

11. Are collected data being analyzed and the results being used?

Yes, manually.

12. A review of any data already collected and analyzed and conclusions from it.

See items 4 and 5 above.

The primary conclusion is that the information already collected has been useful, but the MTBF for components, indeed down to specific parts in specific applications, is desirable to allow routine replacement of parts prior to failure. This is a valid objective for conventional semi-automated, and fully automated transit systems, but it is essential for the latter.

In my opinion, the number of unscheduled maintenance occurrences experienced by PATCO would create untenable service delays in a fully automated unattended transit system. To permit reliable operation of Automated Guideway Transit as a public common carrier, it will be necessary to (1) attain far higher reliability of components than is now experienced, and (2) develop preventive maintenance practices far more effective than are now in use. The cost of these may be very high indeed for an industry that sells low-priced service. Both of the above needs must be filled economically to make Automated Guideway Transit viable.

APPENDICES

1. A typical day's Unusual Occurrences (U.O.) Report, 10/1/76.
2. Scheduled Performance Comparison By Months Report.
3. Car Equipment Activity Report, a typical page.
4. Equipment Activity By Component Report, a typical page.
5. Car and Train Reliability Report, pages 1 and 2, complete.
6. Car Component Performance Report, complete .

PATCO

CAMDEN, N. J.

EQUIPMENT AVAILABLE
A.M. 69 P.M. 69

Oct. 1, 1976

UNUSUAL OCCURRENCES

5:00 AM Oct. 1, 1976 to 4:59 AM Oct. 2, 1976

SCH. TRIPS 320 TRIPS OPR. 328 TRIPS ANN. 0 TRIPS LATE 1 STATIONS BY-PASSED 0

APPENDIX 1

Passenger

- 8:13AM-Report from W/B tr#6 T/O W. Perkins run 105 cars 246-45-202-201-117 at City Hall station that a passenger had fallen on the train and was in need of medical attention. T/O advised to assist as necessary and in the interim, the Cam Cnty Comm. Ctr. was advised and inst. to send an ambul. PATCO Police advised at Brdwy. Mr. L. Quinn advised at City Hall offices and also assisted. At 8:17AM tr#6 was moving W/B with Mr. Quinn aiding the young boy (approx. 10 yrs old) until medical assistance arrived. The boy was then transported to the Cooper Hosp. with his parents, by the Cam. Ambul. Sq. Tr. #6 arr at 16th st 4 1/2 mins late at 8:24 1/2 AM turned & dep. E/B 4 late at 8:27AM and arr at Lind. 8:51 1/2 AM 5 1/2 mins late. No other delays resulted. Additional information on Form SD-501 and Police reports.
Note: T/O Perkins was operating Van ATC at the time and indicated that car 245 (the car the boy fell in) was clean and dry. All involved to submit reports.

NJJ/RBP

*Door 149
Make adjustment
to door &
Com. cables*

- 8:21AM-Report from W/B tr#10 T/O Szabo run 108 cars 239-40-233-34-250-249 at Westmont station that the train had a door problem. T/O inst. check the problem and advise Center of correction made. In the interim, following W/B tr#2 held at 58L signal until problem on tr#10 was corrected. Tr. #10 was moving W/B at 8:26AM and T/O Szabo indicated that he cut out the R-2 door in car 249. Supvrs. O'Nagan and Daniels advised as was Mr. Brown. Tr. #10 arr at 16th st 6 1/2 mins late at 8:42 1/2 AM.
Note: Tr. #13 scheduled to depart Ferry TB at 8:27AM was dispatched O.T. but ahead of tr#10 which it was supposed to follow. Tr. #2 held at 58L until the problem corrected on tr#10 arr at 16th st 4 mins late at 8:46AM.

NJJ/RBP

- 12:33PM-Center Tower reporting that while SEPTA was performing switching operations on the 2854D cable, all lighting (station) and TV monitoring were lost momentarily, with the exception of 13th and Locust, where lighting did not restore, upon completion of switching procedure. Supvr O'Nagan informed. Mr. Quinn at 13th, assisted. (Note: No emergency lighting was available, due to contractor previously disconnecting. Patco Police informed and responded, as well as Phila Sub unit. 12:46PM all lighting returned, with no further problem. Mr. Fiori informed. In the interim, west and east bound trains, were given instructions to by-pass 13th, due to loss of lighting, but plans were not implemented due to return of lighting.
Note: Cause for station lightning not automatically restoring was due to the lighting and power flop-over switch not functioning properly, as per F. Simon

NJJ/RBP

DISPR. ON DUTY:	5 AM - 7 AM	TDB	7 AM - 3 PM	NJJ/RBP	3 PM - 11 PM	TAP. PTD	11 PM - 5 AM	TDB
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WHITE: ASST GM	GREEN: SUPT. OPNS.	YELLOW: SUPT. W & P	PINK: SUPT. CAR EQUIPT.	GOLD: ASST. SUPV. OPNS.
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EQUIPMENT AVAILABLE

UNUSUAL OCCURRENCES

A.M. _____ P.M. _____

5:00 AM Oct. 1, 19 76 to 4:59 AM Oct. 2, 19 76

SCH. TRIPS _____ TRIPS OPR. _____ TRIPS ANN. _____ TRIPS LATE _____ STATIONS BY-PASSED _____

APPENDIX 1 (CONT)

*217
R&R
window*
4. 4:18PM E/B Train #1 T/O A. Philbrick at Ash. Sta. cars (231-32-222-21 217-18) reports that he was advised by a passenger that the 5th car of the train was struck by a large stone ~~W&B~~ while approaching the Haddon T/B. A call was also received via RAX indicating that the stone was ~~THROWN~~ thrown from the S/side of the Right of Way. Both passengers indicated that there were no injuries. PATCO Police (Det. Muckley) was advised, and Supv. U. Raws was advised to check the train upon it's arrival at L'wold. Sta.. Supv. Raws advised C/T that the car was OK to remain in service for the evening loadline, but would be removed from the mainline upon it's arrival at L'wold, at 5:16PM. No delays resulted.

*R&R
Double
check
Valve
&
Air Relay
Valve*
5. 5:45PM. E/B tr. 8, T/O W. Bunting, cars 210-09-246-45-202-01 just east of 16th & Locust. T/O reports possible brake fault. T/O instructed to check train. Supv. Schaffer at 16th advised & responded. 5:50PM. train moving and Supv. Schaffer reports car 245 brake faulted and repairs made by T/O. Supv. further reports air blow between 245/ and 202, brake pipe pulled to correct problem. 6:04PM. Supv. Schaffer reports approaching Ferry ave car 245 rough ride. T/O instructed not to exceed Medium Speed. Supv. Horn at this time rode train @ E/B to L'wold. ConRail advised to hold their tr. 131 due to delay. Two accountable delays resulted in service. T/O tr. 8 arrv. L'wold 6:21PM. 13-mins. late and T/B tr. 9 arrv. 6:24PM. 9-mins. late. P.A. announcements made.

TAP,RED

*135
R&R window
replaced
with new
cylinder
valve.*
6. 11:32PM W/B Tr. 4 car 125 Run 148 T/O L. Blake at Haddon Sta. reports his train was stoned just East of Haddon Sta. and the front window opposite the operator on #2 end was broken. PATCO Ptl. Brown was sitting in the seat but sustained no injuries. PATCO Ptl. Brutshea and Tilton also on train 4 and the 3 pmen were checking the area where the stoning occurred. Tr. 4 was advised to turn the 1st 2 seats over and to continue W/B since the operator advised window not shattered. Tr. 4 departed Haddon at 11:35PM and arrived 16th at 11:52PM 5 min. late and departed E/B at 11:56PM 5 min. late and arrived L'wld at 11:20PM 7 min. late. Supvr. Horn at L'wld advised. T/O Blake instructed to make out incident report. P.A. ann. made about delay. *125 sent to shop.*

tdb

* R & R = Removed and Replaced with a reconditioned unit.

DISPR. ON DUTY: 5 AM - 7 AM 7 AM - 3 PM 3 PM - 11 PM 11 PM - 5 AM

WHITE: ASS'T GM GREEN: SUPT. OPNS. YELLOW: SUPT. W & P PINK: SUPT. CAR EQUIPT. GOLD: ASST. SUPV. OPNS.

APPENDIX 2
PORT AUTHORITY TRANSIT CORP.

SCHEDULED PERFORMANCE COMPARISON
BY MONTHS

DATE	TRIPS SCHEDULED	TRIPS ANNULLED		TRIPS LATE		STATIONS BY-PASSED		% TRIPS NOT RUN / SCHEDULE	% TRIPS RUN / SCHEDULE	
		NO.	%	NO.	%	NO.	%			
TOTAL	1974	102,611	469	0.46%	1229	1.20%	1824	0.18%	1.84%	98.16%
JANUARY	1975	9,099	52	0.57%	236	2.59%	258	0.28%	3.44%	96.56%
FEBRUARY	DERAILMENT 2/14/75	7,973	14	0.18%	132	1.68%	138	0.18%	2.04%	97.96%
MARCH		9,029	20	0.22%	88	0.97%	160	0.18%	1.37%	98.63%
APRIL		8,898	19	0.21%	82	0.92%	108	0.12%	1.25%	98.75%
MAY		9,101	37	0.41%	127	1.40%	171	0.19%	2.00%	98.00%
JUNE		8,200	42	0.51%	133	1.62%	147	0.18%	2.31%	97.69%
JULY		8,045	51	0.70%	135	1.67%	82	0.10%	2.47%	97.53%
AUGUST		8,028	31	0.39%	81	1.01%	96	0.12%	1.52%	98.48%
SEPTEMBER		8,609	68	0.79%	77	0.89%	71	0.08%	1.76%	98.24%
OCTOBER		9,270	22	0.24%	73	0.79%	58	0.06%	1.09%	98.91%
NOVEMBER		8,541	17	0.20%	51	0.60%	70	0.08%	0.88%	99.12%
DECEMBER		8,855	58	0.65%	123	1.39%	135	0.15%	2.19%	97.81%
TOTAL	1975	103,598	437	0.42%	1338	1.29%	1494	0.14%	1.85%	98.15%
	1976									
JANUARY	FERRY AND COLLECTION 1/16/76	8,919	25	0.28%	145	1.63%	168	0.19%	2.10%	97.90%
FEBRUARY		8,183	41	0.50%	177	2.16%	126	0.15%	2.81%	97.19%
MARCH		9,076	48	0.53%	197	2.17%	166	0.18%	2.88%	97.12%
APRIL		8,603	40	0.46%	153	1.78%	54	0.06%	2.30%	97.70%
MAY		8,791	23	0.26%	78	0.89%	119	0.14%	1.29%	98.71%
JUNE		9,214	25	0.27%	134	1.45%	125	0.14%	1.86%	98.14%
JULY		9,677	43	0.44%	115	1.19%	141	0.15%	1.73%	98.22%
AUGUST										
SEPTEMBER										
OCTOBER										
NOVEMBER										
DECEMBER										
TOTAL	1976									

D - 1
 Form Patco - 024, (1-69)

Handwritten: 12/1/74

APPENDIX 3

FACILITY CASE HISTORY REPORT

FOUR WEEKS ENDED AUG 06, 1976

REPORT JWS

ACCOUNTING PERIOD OR

PAGE 1

CAR EQUIPMENT ACTIVITY

CAR NO.	PURPOSE	DESCRIPTION	DEFECT	REPAIR	QTY	TIME	EVENTS
101	4EA0403	INTER SEAT CUSHION ARM RES	DIRTY	CLANFD	0	0.5	1
4FR		INTER OPERATORS CONSOLE	CONSOLE DFFECT	INSPECTED	0	2.0	1
				...NO DFFECT FOUND	0	2.0	1
4F001		DOORS DOOR L.H.	ADJUSTMENT IMPROPER	ADJUSTED	0	1.5	1
4FS1101		DOORS RELAY	DIRTY	BURNISHED	0	1.5	1
4UA0102B		LIGHT LAMP 60W RED LFNS	BURNED OUT	REMOVED AND REPLACED	0	0.5	1
40R4	AS	SIST TRANSPORTATION			0	4.0	2
44R0502		TRUCK WHEEL 2R	RAD CODE 191	WHEELS GROUND ON CAR	0	5.0	1
			WHEEL TRFAD DFFECT	WHEELS GROUND ON CAR	0	5.0	1
441R1A	INSP	INSPECTION SCH FLEC			0	28.0	4
441R2A	INSP	INSPECTION SCH MFCH			0	16.0	2
441X9A	INSP	INSPECTION A			0	0.0	1
446R		CLFAN UNDER CAR AIR BLAST			0	3.0	1

TOTAL NUMBER OF EVENTS FOR THIS CAR = 19 ...TOTAL TIME SPENT ON THIS CAR = 70.5 HOURS

APPENDIX 4

FACILITY CASE HISTORY REPORT

FOUR WEEKS ENDING AUG 06, 1976

REPORT S11

ACCOUNTING PERIOD 08

PAGE 15

EQUIPMENT ACTIVITY BY COMPONENT

FAC. NO.	LOC	PURPOSE DESCRIPTION	DEFECT OR NO DEFECT FOUND REPAIR MADE OR REASON NOT QTY EMP	DATE TIME
202	0 4HM	ATO CAR SIGNAL SYSTEM	CAB SIGNAL FAILURE	TROUBLE SHOOTING 0 07/16 8.0
202	0 4HM	ATO CAR SIGNAL SYSTEM	INTERMITTENT	TROUBLE SHOOTING 0 07/16 4.0
991	0 4HM	ATO CAR SIGNAL SYSTEM	WIRING DEFFECTIVE	REWired 0 08/03 2.0
991	0 4HM	ATO CAR SIGNAL SYSTEM		0 08/03 8.0
992	0 4HM	ATO CAR SIGNAL SYSTEM	WIRING DEFFECTIVE	REWired 0 08/03 2.0
202	0 4HM01	ATO MASTER DECODER RELAY	CAB SIGNAL FAILURE	REMOVED AND REPLACED 0 07/16 0.0
	0 4HM0201E06ATO	RIVET	PROGRAMMED MAINTENANCE	PERFULT 0 07/14 8.0
201	0 4HM09	ATO AMPLIFIER	WILL NOT OPERATE	REMOVED AND REPLACED 0 07/14 0.0
202	0 4HM09	ATO AMPLIFIER	INTERMITTENT	REMOVED AND REPLACED 0 07/16 6.0
991	0 4HM14	ATO RUZZER	WILL NOT OPERATE	REMOVED AND REPLACED 0 07/30 0.5
992	0 4HM14	ATO RUZZER	WILL NOT OPERATE	REMOVED AND REPLACED 0 07/30 0.5
991	0 4HS	ATO TRAIN IDENTIFICATION	MISCELLANEOUS DEFECTS	MISCELLANEOUS REPAIRS 0 08/07 4.0
992	0 4HS	ATO TRAIN IDENTIFICATION	MISCELLANEOUS DEFECTS	MISCELLANEOUS REPAIRS 0 08/07 4.0
239	0 4HS0202	ATO CAR BORNE CONTROL RO	WILL NOT OPERATE	TROUBLE SHOOTING 0 07/13 1.0
239	0 4HS0202	ATO CAR BORNE CONTROL RO	ADJUSTMENT IMPROPER	ADJUSTED 0 07/13 1.0
234	0 4HW	ATO STATION STOP DETECTI	WILL NOT OPERATE	TROUBLE SHOOTING 0 07/13 0.5
234	0 4HW	ATO STATION STOP DETECTI	ADJUSTMENT IMPROPER	ADJUSTED 0 07/13 0.5
111	0 4NA	A C AIR CONDITIONING	H LFAKING	SEALED 0 07/20 8.0

APPENDIX 5

CAR EQUIPMENT REPORT

FOUR WEEKS ENDED AUG. 06, 1974
ACCOUNTING PERIOD 08

REPORT JWS
PAGE 3

CAR AND TRAIN RELIABILITY

CAR NUMBER	MILES TRAVELED THIS ACCT. PD.	HOURS ON THE LINE	NO. COMPONENT FAILURES	MEAN TIME BETWEEN MALFUNCTION COMPONENTS	HOURS OF MAINT TIME	HRS ON THE LINE PER HR OF MAINT
226	5113.	57.1	1	57.1	27.0	2.1
227	5419.	151.8	1	151.8	11.0	13.8
228	5619.	151.8	3	50.6	17.0	8.9
229	5241.	141.6	1	141.6	2.5	56.6
230	5241.	141.6	6	23.6	14.5	9.7
231	3773.	101.9	2	50.9	17.0	5.9
232	3773.	101.9	7	14.5	41.0	2.4
233	4742.	128.1	3	42.7	25.5	5.0
234	4742.	128.1	3	42.7	14.5	15.0
235	3603.	97.3	1	97.3	3.0	32.4
236	3603.	97.3	2	47.6	10.0	9.7
237	4291.	115.9	4	28.9	21.0	5.5
238	4291.	115.9	4	28.9	15.0	7.7
239	2143.	57.9	3	19.3	31.0	1.8
240	2143.	57.9	1	57.9	5.0	11.5
241	4764.	128.7	2	64.3	1.0	128.7
242	4764.	128.7	2	64.3	1.0	128.7
243	4655.	125.8	2	62.9	8.0	15.7
244	4655.	125.8	1	125.8	21.0	5.9
245	4071.	131.6	4	32.9	30.5	4.3
246	4071.	131.6	5	26.3	28.0	4.7
247	4065.	134.1	4	33.5	44.0	3.0
248	4065.	134.1	4	33.5	25.5	5.2
249	2242.	60.5	2	30.2	5.0	12.1
250	2242.	60.5	1	60.5	3.0	20.1
DOWNFST AVG.						16.3
3099.						109.0
3.0						56.7
26.5						16.3
SYSTEM AVG.						17.1
4242.						114.4
43.6						32.5
17.1						17.1

FACILITY CASE HISTORY REPORT

CAR COMPONENT PERFORMANCE

FOUR WEEKS ENDED AUG 06, 1976
ACCOUNTING PERIOD 08

APPENDIX 6

REPORT JW4
PAGE 1

CODE	DESCRIPTION	NO. OCCURRENCES	PERCENT OF TOTAL	REPAIR TIME	PERCENT OF TOTAL
4A	EXTERIOR	8	0.53	8.00	0.16
4C	COUPLER EQUIPMENT	31	2.06	52.00	1.07
4D	WINDOWS	20	1.33	36.00	0.74
4E	INTERIOR	73	4.86	88.50	1.82
4F	DOORS	118	7.86	195.50	4.03
4G	DOOR CONTROLS	18	1.19	27.50	0.46
4H	ATC-ATO	35	2.33	120.00	2.47
4N	AIR CONDITIONING--HEATING	42	2.79	117.50	2.42
4Q	COMMUNICATIONS	20	1.33	25.00	0.51
4R	M.G. SFT	64	4.26	141.00	2.90
4S	MISC. ELECTRICAL	2	0.13	3.00	0.06
4T	MASTER CONTROLLER	19	1.26	68.00	1.40
4U	LIGHTS	85	5.66	73.50	1.51
4V	DESTINATION SIGNS	17	1.13	17.00	0.35
4W	MISC. BODY	12	0.79	19.00	0.26
4Y	ACCELERATING RESISTOR	2	0.13	12.00	0.24
42	CONTROLLER	28	1.86	56.50	1.16
43	CAM CONTROLLER	56	3.73	108.00	2.22
44A	WORK TRAIN	6	0.39	22.00	0.45
44B	TRUCK	180	11.99	430.50	8.87
441	PERIODIC MAINTENANCE	423	28.18	1970.50	40.62
446	CLEANING	87	5.79	586.00	12.08
45	AIR BRAKE SYSTEM	73	4.86	131.00	2.70
TOTALS		1419	94.53	4297.00	88.59

In the appendix, you'll see, we have several printouts. Now, every maintenance activity or occurrence is entered on a Defect Report. First of all, Operations turns in a card with a symptom; then it's given to a foreman, either mechanic or electrical or electronic, who assigns it to a worker or a team of workers, one of whom will be the lead man with the paper work. He, or they, will correct the problem and arrange the number of tenths of hours they worked on it, the material they used, and various other things that were noted. We have two basic printouts which were designed by accountants for accountants, and they do not give me the information I'd like to have. But, nonetheless, they're a historic reference. Each occurrence or line item in there is one action done by one man. So, if you look on one report, you'll see cars 201 and 205 five times on the same day for various aspects of cab signal failure. Two men worked on that; they did three different things which generated five line items. So, on some of our summaries it looks like five things happened. Actually, it didn't; it was one event. Two people did three things in the course of half a day, and you end up with five line items. I know that; an outsider may not. At least I'm dealing with the same measure each month, so that I can identify trends.

Another printout does summarize things somewhat. Two years ago I was able to persuade the General Manager to let me hire a graduate student to work one summer for us, and he took these two basic printouts. One he did by car number, and the other by component subsystem. We aggregated the car number one to come up with what is shown in Appendix 5, where we show miles traveled this accounting period, a four-week period; hours on the line, which is miles divided by 39, our average speed; and number of component failures. We say component failures, because in most cases the car didn't fail; it continued to run, but it came off the line at the end of its tour for that day. But sometimes the car does have to come off the line, and the circumstances will vary. If it's a one-car train running after 7:00 p.m., and its motor-generator fails, the car's dead, and it has to be pushed by its follower out of service once it's run its battery down.

The battery will give him about a half hour, which is usually enough to get back, but it may not. However, if it's one car in a six-car train, the cars next to it will carry the load. So, the same failure has different repercussions, depending on the time and place. Therefore, we don't count the incidents where trains are removed from service. All I'm concerned with, as the Equipment Superintendent, is that the equipment doesn't fail. The fact that the failure causes different problems to Operations is no concern of mine directly. If it didn't fail at all, they would have no problem, so it's my problem to fix it. So we have mean time between component malfunctions and hours, and hours in maintenance time devoted to that car; then the last thing is hours on the line per hour of maintenance. The time intervals involved in these records vary quite widely. One serious fault will consume maybe 100 hours or more. But typical problem takes about 2-1/2 hours to correct.

The very last page of the Appendix 6 is the summary by subsystem, so that I can tell, on an overall basis, where our efforts have gone. You see item 441, periodic maintenance, and item 446, cleaning. Those two items are the only scheduled activity. We're consuming about 53% of our man-hours on things that we plan on. On item 4N, air conditioning, a certain amount of that is scheduled for maintenance; I have to subdivide that into corrective and other maintenance. But generally speaking, you can see the relative weight of the way the numbers fall.

Doors you have also heard about, and I can only endorse the statements. Doors must be improved. However, we haven't given it a whole lot of effort, because while there are a lot of incidents, they don't cause a whole lot of trouble. There are other doors in the car. If one of them doesn't work, we shut it off until we get to the end of the line. We bring it down to the shop, and it usually takes about 15 to 30 minutes to correct it.

Now, how effective are failure management systems in reducing passenger delays? As I mentioned, our analysis is manual; we have a very close relationship to our rolling stock. My office is

literally 30 feet from where the cars are fixed. If there's something wrong, something unusual, I know about it instantly. Usually, a foreman or technician comes to the door and says, "Boss, take a look at this one, we never had this before; it couldn't happen but it did." We do respond quickly to most events. Now, what would I like? I would like to find mean time between failure. I think we have the raw data we need. I have made my interest known to Mr. Boyle of UMTA. Carnegie-Mellon is currently seeking a place to implement such a pilot program. I attended Carnegie-Mellon last year. I learned the program and got to know Dick Uher pretty well. He surveyed our property, and next year we're planning to implement a RAMS (Reliability, Availability, Maintainability, Safety) system, about a two-year effort. Our objective, of course, is to replace certain components at about 80% of their service life, so that we'll have a much smaller number of failures on the line.

Now, as to the question, is a passenger delay measure of service availability possible? Yes, I think it is. Now, we have an automatic fare collection system at unattended stations. A passenger buys from a vending machine, or from the newsstand, a magnetic controlling card. We sell it by the ride, as does the Illinois Central Railroad, both for suburban and zone systems — BART, Washington, Metro will follow and Miami and Atlanta are still thinking of what they're going to do. Perhaps they will use a store value system where you buy a ticket worth a certain amount of money, and then the automatic fare collection system deducts the value from your ticket each time you use it. It's necessary, with these forms of zone or distance fare collections to check people into and out of the system through a gate. The process consists of an electronically read ticket, electronic calculations, and then an electromechanical device to open and shut the gate. So, the means exist to know how many people are in the system at any given moment, and where they get in and where they get out. I believe this could be linked to a central computer in the control center. Right now, we do have data lines, but it's used for remote control. We can read a ticket remotely

and take corrective action-let people through the system with under-value tickets after they pay the excess fare, or take care of certain data defects on a ticket, or simply let people in or out for other purposes. So, the data link exists; we have modems at each end. It would not be conceptually too difficult to count everybody coming in and going out. Each pair of points could be given a standard running time. I think this would be possible. Anybody exceeding this statistic would be considered a delayed person. I don't think this would be too hard for a system with a central computer. Implementing it with a system with lots of stations and lots of station pairs makes it rather cumbersome, but in my opinion it is quite possible.

Now, we don't measure this ourselves. We just intuitively know that if a delay happens at 4:55 p.m. in the Philadelphia subway, we have problems. If it happens at Lindenwold terminal at any time before about 3 minutes before the train's departure, we can replace the train with another one, and it goes out with no particular problem. Thus, where something happens, and when it happens, are crucial to how it affects passengers. The identical technical fault will have tremendously varying impact on the system, and for that reason I don't really think the passenger delay measure is worth doing. We don't do it, and I wouldn't recommend that we spend the money to do it. So, that's my answer to that particular question.

What data are collected for reliability and maintainability? I've talked to you about out printouts. These are analyzed, the results are being used absolutely, and it's all done manually, and by a hierarchy of what's important, and what's causing us the trouble. In a couple of cases, though we have identified the problem, we have been unable to come up with a solution. We have a Morgan generator, which converts 700 volts dc line voltage to 37-1/2 volts dc for battery use in the auxiliary powered components in the car. Thus far, GE has gone through about four different things they said would fix it, and the statistical results are that it remains the same. So you have to do something after you know about it. In many other cases,

though, our own engineer, who is extremely useful and dedicated and intelligent, has fully corrected a number of subsystems which gave us considerable trouble. The failures are now down to practically a nil level, a few a month, and these are easily coped with.

(End of Paper 5 Presentation)

Mr. Vigrass

That's the end of my discussion. If there are any questions to myself or anyone, we'll be glad to entertain them.

Mr. Gardner

What can you say about your add fare system?

Mr. Vigrass

It was developed when we first went to the unattended station concept. A Consultant wrote a specification for something he called a speaker phone which was intended to be rather like an apartment house unit. When you put coin slots in it, it would register coin values and transmit them to our control center, and then the passenger could go back through the gate via a gate control. He could find no one interested in building 12 of these units. They might be interested in 1,200, but for 12 they simply ignored it. So, we decided to obtain some used telephones. We contacted a local surplus house in Camden, New Jersey, and we found some old Stromberg-Carlson pay telephones we bought for \$55 a piece, and put them through our communications shop. At a total cost of \$125 apiece, we put in these old 1939 pay telephones at each station by the gates. Now with the present procedure the passenger comes to the gate, puts his ticket in, and it comes out and says, "Call for a defect 3." Now, we know and the Supervisor knows that defect 3 is an undervalue ticket. To the passenger it says call for aid. There's a big sign that says, "Call for Aid on this red telephone." He goes over and dials 11, and says, "I can't get out of this place." The TV operator pushes his update button for that station and says, "Where are you?" He

says, "I'm at West Line." The operator pushes the button, and the gate then transmits to the center tower the last ticket that went through it. It's displayed as a row of lights representing the bit pattern on a ticket. There is a group of old cards above. The bits are matched up and the message comes through, "You have a ticket for Philadelphia-Camden, and you paid 50¢ for it. You owe me a quarter. Please put 25¢ in the telephone. The operator says, "All right, thank you, sir, now go back to the first gate and I'll let you through. Put your ticket in in a normal manner." So he goes back, she hits the one that says, "Override zone defect." Providing the ticket is otherwise good, it's still got a ride left on it, and it's good for exit and not entry, it says, "Okay, now you can go through." A light comes on and says "Go." The turnstyle unlocks, the person goes through, we've got the quarter, he's out of the station, the ticket's been captured, and the transaction is complete. It's a little bit clumsy, but it doesn't happen very often; we have an average of 30-50 add fare transactions per day.

Mr. DeMarco (UMTA)

I'd like to poll the panel on one point on reliability that has to do with multiple cars versus single cars. Does the availability of a train improve when you have one car, two cars, four cars or six or ten cars on a train, or does it go down?

Mr. Vigrass

The chances of a defect occurring absolutely increase by the number of cars. However, the chances of needing to take the train out of service are greatly reduced. I've heard that in the New York City Transit System anytime they check the system, they find around 10% of the cars in the runway system are dead. But they're eight- or ten-car trains, and nobody knows it unless he looks. Now, we can run a train with one, or even two, cars dead with hardly a discernible degradation of service. It overloads the motors on the other ones, and you don't do it for more than one trip. We get an indication, incidentally. In our system,

we get a red light in the cab if there's a car dead on the train. However, the train continues to operate. Its rate of acceleration is a little bit degraded, but its top speed is the same. So, in that sense, it's no problem. But there are other kinds of faults. We have an electro-pneumatic brake system, which is a pretty common setup these days. It's an analog system with braking in proportion to the current, not the voltage, on a wire between zero and 1 amp. If that is grounded anywhere on the train, the brakes are applied. Then you have to find the car that's grounded and cut it out. On that fault, the more cars you have on the train, the more chances you have for that kind of fault.

So, I have to answer your question in two ways. It depends on the fault you're talking about. In some cases you can continue running; in other cases you multiply the chances of stopping the train. In this train reliability report, we generate curves each month. As for the chances of two- and six-car trains, either singles or doubles, running until a defect occurs, the two-car train gets down to 80% chance of having a defect at the 27th hour, and the six-car train reaches it about the 22nd hour. And that is a defect requiring corrective action but not necessarily requiring the train to be pulled off the line. About one or two out of ten defects cause us to pull a train out of service. With most of them we can run until the end of the duty assignment.

So, again, there's not a definite answer to your question. But we did conduct a test. When we started generating the data, and the data was selected by the computer, by car number on the best train and the worst train for each category, we actually put a six-car train out on the line with the car numbers that the computer gave us, and it ran for exactly 20 hours, and it came in with one car dead. The contractor had welded on that car, and the dynamic braking was not working. Now, the car still performed all right, but it was not running correctly. And that's what we define as a defect - something not performing in accordance with the specification. I believe Max and people here also defined it similarly for their system.

Mr. King (BART)

If I had the option on BART, I would run nothing but two-car trains, and then expand them only to the degree necessary to carry the number of passengers I need to carry. But if I had the option to design the system, I think my answer would be different. We don't even begin to utilize the tremendous redundancy built in there, and to me it's unreasonable. I've seen trains running with six train control systems on it (Sao Paulo). Somewhere along the line somebody once had an idea that there should be an operator up front to run the train. But if we look at the front train control system, we see that train control system runs the train. The train control doesn't care; if it faults, it switches to the next one. Redundancy was designed into the system. If you've got seven cars there, you ought to be able to get power into the cars that fail. The possibility of increasing transportation availability by use of that inherent redundancy is fantastic.

Mr. Vigrass

I think that eventually we'll be able to do just that; designate any one of them as a lead car, and the rest of them continue to function. We can't do it now.

Ms. Judith Gertler (TSC)

Bill, in your discussion you addressed the issue of informing passengers about the cause of a delay or inconvenience. I was curious to know how the other systems represented here on the panel handle this issue.

Mr. Vigrass

How are passengers advised of delays on the other systems?

Mr. King

At BART, when a delay is in process, the central agent can dial stations and make an announcement to people on the platform. The train control operators are notified, and are supposed to use reasonable judgment in notifying the passengers.

Mr. Vigrass

We do it with radio from Central Control. We keep the passengers notified that there'll be a slight delay, or that they're going to be escorted off the car on foot, whatever the conditions might call for.

Mr. Ochsner (AIRTRANS)

On AIRTRANS, for short delays we make a specific announcement to the train or trains that are being delayed, and also to the stations affected. If it's a major situation, we can make both an all-trains announcement and an all-stations announcement.

Mr. Bissett (CTA)

Depending upon the type of problem, we try to make announcements where we can, but in general the number of events that occur during the day and the number of people available to make these announcements preclude us doing so on all but quite large delays. Working at the line log, we do have provision for doing it--We have train phone on the trains, and carry our system on the third rail. And the rail controller can call the motormen and give them a 1077, as we call it; motormen can then connect the PA system on board the train to the train phone, so that the rail controller downtown can make the announcement directly to the passengers on the train. We also have PA speakers at certain stations, particularly the stations where we have the train dispatching equipment which are terminals, and a few midpoints and downtown subway stations have speakers through which announcements can be made. In general, the announcements are not made until the delay gets upwards of 10 or 15 minutes. In certain instances the people on the train are fully aware of it, anyway, and they don't bother with making announcements. For instance, one example relates to a disturbance on a two-car train, occurring in the midnight hours. Everybody can see through the trains fairly well because there are enough windows on the train, and so everybody on board the train will be fairly well aware of what's going on. They see the police come, arrest the man, and take him off the train. In such a case they don't bother making an announcement.

Mr. Pawlak

I've always been pleased that PATCO does, in fact, publish its schedule. So, in a way there is a contact between the supplier and the user, and a definite expectation on the part of the user. You've chosen four minutes as a threshold of what you can call late and what's not. You have a good feel for the distribution of delays figured in four minutes, so that you know how fast that drops off.

Mr. Vigrass

The raw data exists to have that calculated rather readily; it's just that I have never seen it done. It wouldn't be hard to do it. Actually, our choice of a four-minute threshold is arbitrary. Our line is short, our running time is only 23 minutes, so four minutes is a high percentage. Maybe we're being too generous to ourselves. But we found that it is a number that reflects pretty well when a passenger starts getting irritated.

Question from Audience

Does four minutes represent the maximum delay time, or is it time late at the arriving terminal?

Mr. Vigrass

It's late at the terminal. Even if it entails some cost, it's good public relations.

Mr. Pawlak

The other question I have for you is this. You mentioned earlier that you were buying an additional 46 cars. To what extent have you made use of your experience and asked for specific reliability requirements or maintainability requirements in terms of numerical values?

Mr. Vigrass

In terms of numerical values, not much. As for changes in specific hardware, yes. In some cases we didn't say what we wanted; we merely said that what we got was not good, and to bring us something else. And in several subsystems the specs said that the Authority retains the right of detailed design review. We didn't know what they were going to propose. We just tried to protect ourselves, not knowing what we were going to get into. It's rather imperfect, I think. Our consultant did do an analysis, a year ago, of all the data we had. He generated a voluminous report recommended the specific changes in the car design, and they spent a fair amount of time on it. I believe most of it is basically realistic and good, and in keeping with commercial expectations.

Mr. Pawlak

And it is meant to be a close match for the fleet you've got.

Mr. Vigrass

Yes. If we get what we want, it'll be about 85% the same; and the 15% differences are those we positively want.

(End of Panel 2 Session)

PANEL 3

THEORETICAL ASPECTS OF AGT SERVICE AVAILABILITY

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The third panel session began with an introduction by Mr. Watt of the chairman for the third panel proceedings, Dr. J. Edward Anderson, of the Universtiy of Minnesota.

Mr. Watt

The third panel today is to look at more theoretical aspects of automated guideway service availability. You see before you a rather powerful panel headed by Ed Anderson, Professor of Mechanical Engineering at the University of Minnesota. He received a PhD Degree in Aeronautics and Astronautics from MIT. His teaching is primarily in the field of transit systems and transit systems analysis, so he has a good background for the kind of thing we'll be talking about this morning. He's been the Chairman of the International Conference on Personalized Rapid Transit for the last several years. He's President of the new organization called the Advanced Transit Association, which is just getting started. He has been on leave from the University of Minnesota for two years, initially with the Rapid Transit District in Denver, and then more recently with Raytheon. He's now back at the University of Minnesota. I'll turn the meeting over to Ed Anderson, who will carry on for the rest of the morning.

Dr. Anderson

Thank you, Chan. For most of you who like to keep track of who's speaking when, the order of the speakers will be as follows. I'll speak first. As panel chairman, maybe I should have picked myself to speak last, but I think that the kind of theory that I'm going to present would appropriately come first. Second will be Dr. Womack; then we'll hear from Lee Tucker, Oglesby, Roesler, Doyon, and Diamant, and we will finish with some concluding remarks.

When I worked at the Denver RTD I could see that a theory for system reliability requirements was very urgently needed, and, while with Raytheon last winter, I had a little time to develop such a theory. What I'm going to present you is the beginning of a scheme; it's not complete in any sense, but the basic theoretical framework is there. It makes use of fundamental mathematical work of the very famous French mathematician Lagrange, who lived from the middle of the eighteenth century to the early part of the nineteenth. The basic techniques have been in the literature for a long time, but this is the first time I've had a chance to apply Lagrange's equations to a transit-related problem.

PANEL 3

PAPER 1

LIFE-CYCLE COSTS AND RELIABILITY
ALLOCATION IN AUTOMATED TRANSIT
SYSTEMS

J.E. ANDERSON

LIFE-CYCLE COSTS AND RELIABILITY ALLOCATION
IN AUTOMATED TRANSIT SYSTEMS
J. E. Anderson*

1. Introduction

The life-cycle cost of a system is the sum of the acquisition cost and the support cost. The acquisition cost is the purchase price plus the interest cost; and the support cost is the cost of labor, equipment, spare parts and the associated logistics required to operate the system and to keep it in operation during its useful life. The acquisition and support costs of transit systems, in particular, vary widely, depending on the proximity of a large number of parameters to optimum values. In this paper, the problem of optimization of the reliability of automated transit systems with respect to life-cycle cost is considered.

In a given transit system, defined by the types of components used and the service provided, the acquisition cost will generally increase with the built-in reliability of the components and subsystems, as shown in Figure 1. On the other hand, the support costs reduce as reliability increases because the frequency of maintenance declines. Thus the life-cycle cost exhibits the character of a U-shaped curve with a single minimum point. Each subsystem, such as a motor, a controller, a braking system, or a wayside computer also possesses a similar life-cycle-cost curve. If each subsystem is designed so that its life-cycle cost is minimum, the system life-cycle cost is a minimum. If the system reliability is adequate at minimum life-cycle cost, no further analysis is needed; however, the more usual situation is that in which system reliability must be improved. The problem then presents itself as to how to allocate subsystem reliabilities in such a way that the system life-cycle cost is minimized at the required level of

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system reliability. This is a standard Lagrangian minimization problem, the solution of which is the main subject of this paper.

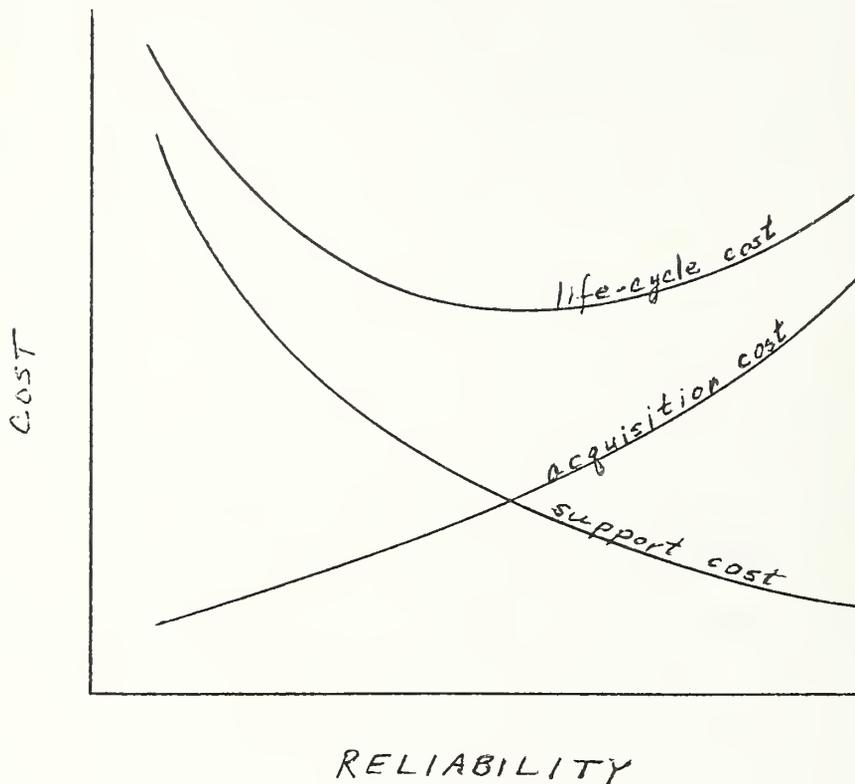


Figure 1 Life-Cycle Cost

To solve the minimization problem in a meaningful way for transit systems, it is necessary to define a meaningful and accepted measure of system reliability, and to establish a means of classification of failures. System reliability is commonly measured in terms of "availability," and is treated in the next section. Classification of failures then follows.

2. Availability and Unavailability

Service availability in transit systems has been the subject of a great deal of analysis; however, at the time of writing no completely accepted methodology has developed, nor can it develop without considerably more operational experience with automated systems. Nonetheless, a logical formulation is possible which can be described in enough detail for the purpose of this paper. The common definition of transit-system availability is the ratio of the nominal trip time to the nominal trip plus the average time delay due to failures. To take into account variations in availability in various parts of the system at various times of day and on various days, the following definition of service availability A is more suitable:

$$A = \frac{PH_{yr}}{PH_{yr} + PHD_{yr}} \quad (1)$$

in which PH_{yr} is the number of passenger-hours of travel per year on the transit system, and PHD_{yr} is the number of passenger-hours of delay due to failures per year.

Define "unavailability" as

$$\epsilon = \frac{PHD_{yr}}{PH_{yr}} \quad (2)$$

In a perfect system, ϵ vanishes. If $\epsilon \ll 1$, as it must be if the system operates satisfactorily, equations (1) and (2) gives

$$A = \frac{1}{1 + \epsilon} \approx 1 - \epsilon \quad (3)$$

Thus, the sum of availability and unavailability is practically equal to one. Unavailability is the more useful measure of system performance because, as shown in Section 5, it is the weighted sum of failure rates, and such a formulation is advantageous in the solution for the constrained minimum life-cycle cost.

The quantity PH_{yr} can be expressed in the form

$$\begin{aligned}
 PH_{yr} &= (\text{Person-Trips/yr})(\text{Average trip time}) \\
 &= (\text{Equivalent work days/yr})(\text{Trips/work day}) \frac{\langle L_t \rangle}{v_{av}} \\
 &\approx 300t_d \frac{\langle L_t \rangle}{v_{av}} \qquad (4)
 \end{aligned}$$

in which t_d is the number of trips in an average work day, $\langle L_t \rangle$ is the average trip length, and v_{av} is the average trip speed.

In the form given by equation (4), PH_{yr} is directly obtained from data normally available. A meaningful expression for PHD_{yr} depends upon the following definitions of subsystems and classes of failure.

3. Subsystems of an Automated Transit System

To make the analysis specific and therefore more meaningful, consider that an automated transit system will generally contain the types of equipment listed below:

Basic Components (without listed subsystems):

1. Vehicles
2. Guideways
3. Stations

Vehicle Subsystems:

1. Automatic vehicle door
2. Propulsion system
3. Control system including sensors and actuators
4. Power conditioning and/or supply system
5. Braking system
6. Switching system
7. Failure-detection system

Wayside Subsystems:

1. Passenger processing equipment in stations
(fare collection, destination selection, ticket vending,
turnstiles)
2. Automatic station doors
3. Station-entry monitors
4. Station-operated vehicle dispatchers
5. Merge-point communication and control units
6. Diverge-point communication and control units
7. Wayside switches
8. Wayside vehicle-presence sensors
9. Wayside-to-vehicle, vehicle-to-wayside communication equipment
10. Central empty-vehicle dispatcher
11. Central trip register and dispatcher
12. Central power supply

4. Classes of Failure

Each subsystem may, in general, fail in ways which produce different consequences in terms of the average number of passenger-hours of delay. These different modes of failure will be defined as different "Classes of Failure," and they need to be distinguished in this analysis in order to compute the number of passenger-hours of delay, and then the unavailability.

Some examples of classes of failure are the following:

Vehicle failure classes:

1. Vehicle is permitted to continue to nearest station, where passengers must egress. Vehicle is dispatched to maintenance. The number of passenger-hours of delay is the time lost by P_v passengers in transferring to second vehicle.
2. Vehicle is required to reduce speed but is permitted to continue to nearest station, where passengers must egress. Vehicle is dispatched to maintenance. The number of passenger-hours of delay is as computed in Class 1 plus time lost by people in a string of vehicles required to slow down while the failed vehicle advances to nearest station.
3. Vehicle stops or is required to stop and is pushed or towed by adjacent vehicle to nearest station. After people in the two affected vehicles egress, failed vehicle is pushed or towed to maintenance. The number of passenger-hours of delay is computed as in Class 2 but time delay is longer.
4. Vehicle stops and cannot be pushed or towed by adjacent vehicle. Must wait for rescue vehicle. The number of passenger-hours of delay is computed as in Class 3 but the total time delay is much longer and depends on the availability of alternative paths.

Merge-point command-and-control-unit failure classes:

1. Vehicles can proceed through merge point at reduced speed.
2. Vehicles must stop until unit is repaired.
3. Collision occurs.

Diverge-point command-and-control-unit failure classes:

1. Occasional vehicle is misdirected.
2. Entire stream of vehicles is misdirected.

5. Passenger-Hours of Delay per Year and the Unavailability

Let p = the number of different subsystems, as identified in Section 3.

q_i = the number of classes of failure of the i -th type of subsystem.

r_i = the number of i -type subsystems in the transit system

T_i = the number of hours the i -type subsystems are in service per year. If the subsystem is aboard a vehicle, T_i is the number of hours per year a vehicle is in service.

Let this number be T_v . Typically T_v is about 10 hrs/day times 300 days per year, or 3000 hrs/yr. If the subsystem is at wayside and the system operates 24 hrs per day,

$T_i = T_w = (24)(365) = 8760$ hrs per year. If the system operates say six days a week and 18 hrs per day,

$T_w = 5616$ hrs per year.

$MTBF_{ij}$ = mean time between failures of the j -th class of the i -th type of subsystem

The MTBF of interest in transit systems is that which occurs due to random failures of maintained equipment. Unlike a spacecraft, a transit system can and should undergo periodic checks at a frequency greater by a factor of at least five than the failure rates to diagnose potential failures and to replace components that wear out. The time intervals between preventive diagnostics and maintenance are therefore short compared to the MTBF's. In this circumstance, the probability of failure in a given time increment is not strongly a function of time and can be assumed, in the service interval, to be random. Then the number of j-class failures per year of a piece of i-type equipment is simply r_i / MTBF_{ij} , and the total number of failures per year is

$$\sum_{i=1}^P \sum_{j=1}^{q_i} \frac{r_i T_i}{\text{MTBF}_{ij}}$$

Let τ_{ij} be the mean time delay of a person involved in a j-class failure of i-type equipment, and let n_{ij} be the mean number of people involved in such a failure. Then $n_{ij}\tau_{ij}$ is the mean number of person-hours of delay due to a j-class failure of i-type equipment. Thus,

$$\text{PHD}_{\text{yr}} = \sum_{i=1}^P r_i T_i \sum_{j=1}^{q_i} \frac{n_{ij} \tau_{ij}}{\text{MTBF}_{ij}} \quad (5)$$

As indicated in the definition of T_i , there are generally two values for T_i , T_v for vehicle-bourne equipment and T_w for wayside equipment. If there are N_v vehicles in the system, equation (5) can be written

$$PHD_{yr} = N_v T_v \sum_{i=1}^{p_{vs}} \sum_{j=1}^{q_i} \frac{n_{ij} \tau_{ij}}{MTBF_{ij}} + T_w \sum_{i=p_{vs}+1}^p r_i \sum_{j=1}^{q_i} \frac{n_{ij} \tau_{ij}}{MTBF_{ij}} \quad (6)$$

in which p_{vs} is the number of types of vehicle-bourne subsystems, and $p_{ws} = p - p_{vs}$ is the number of wayside subsystems. The unavailability is now obtained by substituting equations (4) and (6) into equation (2).

6. The Constrained Minimum Life-Cycle Cost

The life-cycle cost of a system is the sum of the installed costs of all subsystems plus the sum of the operating and maintenance (support) cost of all subsystems. Thus it is possible to express the life-cycle cost (LCC) in the form

$$LCC = N_v \sum_{i=1}^{p_{vs}} LCC_i(x_{ij}) + \sum_{i=p_{vs}+1}^p r_i LCC_i(x_{ij}) \quad (7)$$

in which $x_{ij} \equiv \text{MTBF}_{ij}$ and the functional dependence of subsystem life-cycle cost on reliability is explicitly indicated, i.e., LCC_i is a function of the MTBF's for all classes of failure associated with i-type subsystems.

The problem posed is to minimize LCC subject to a constraint--the given value of ϵ , where ϵ is a function of all x_{ij} . To find the constrained minimum, a problem first solved by the French mathematician Lagrange (1736-1813), assume that ϵ is solved for one of the x_{ij} , say x_{mn} . Then, in principal, substitute x_{mn} , a function of all of the other x_{ij} , into LCC. In this case, the condition that LCC is minimum is

$$\frac{\partial \text{LCC}}{\partial x_{ij}} + \frac{\partial \text{LCC}}{\partial x_{mn}} \frac{\partial x_{mn}}{\partial x_{ij}} = 0 \quad (8)$$

in which i and j take all values in the ranges $j = 1, \dots, q_i$ and $i = 1, \dots, p$ except for the single combination of values $i = m, j = n$. Since $\epsilon = \epsilon(x_{ij})$ is a given constant,

$$\frac{\partial \epsilon}{\partial x_{ij}} + \frac{\partial \epsilon}{\partial x_{mn}} \frac{\partial x_{mn}}{\partial x_{ij}} = 0 \quad (9)$$

for all i, j except m, n .

Place the right-hand term in each of equations (8) and (9) on the right side of the equal sign and divide equation (8) by equation (9). The result can be expressed in the form

$$\frac{\frac{\partial LCC}{\partial x_{ij}}}{\frac{\partial \epsilon}{\partial x_{ij}}} = \frac{\frac{\partial LCC}{\partial x_{mn}}}{\frac{\partial \epsilon}{\partial x_{mn}}} = -\Lambda \quad (10)$$

in which, because x_{mn} could be any of the x_{ij} , Λ has the same value for all ij . The constant Λ is called a Lagrangian multiplier.

From equation (7),

$$\frac{\partial LCC}{\partial x_{ij}} = r_i \frac{\partial LCC_i}{\partial x_{ij}} \quad (11)$$

in which $r_i = N_v$ if the index corresponds to a vehicle subsystem.

Similarly, from equations (2) and (5) ($x_{ij} \equiv MTBF_{ij}$),

$$\frac{\partial \epsilon}{\partial x_{ij}} = - \frac{r_i T_i n_{ij} \tau_{ij}}{PH_{yr} x_{ij}^2} \quad (12)$$

Substituting equations (11) and (12) into equation (10), the Lagrangian multiplier becomes

$$\Lambda = \left(\frac{PH_{yr}/T_i}{n_{ij} \tau_{ij}} \right) MTBF_{ij}^2 \frac{\partial LCC_i}{\partial MTBF_{ij}} \quad (13)$$

in which the substitution $x_{ij} \equiv MTBF_{ij}$ has been made, and $T_i = T_v$ or T_w depending on the location of the equipment. The solution to the problem of the constrained minimum life-cycle cost is determined by the condition that the quantity defined by the right side of equation (13) is the same for all failure classes of all subsystems.

Equation (13) contains three kinds of factors:

- 1) PH_{yr}/T_i is the number of person-hours of travel on the system per hour of operation of i -type equipment, a factor determined from an understanding of the physical characteristics of the system and from an estimate of patronage.
- 2) $n_{ij} \tau_{ij}$ is the number of person-hours of delay due to a j -class failure of i -type equipment. It is a matrix of values determined from classification of all failure modes, from estimation of the mean delay time due to each failure mode, and from estimation of the mean number of people involved in each failure mode. The later factor, n_{ij} , is proportional to patronage, but since PH_{yr} is also proportional to patronage (see equation (4)), Λ is independent of patronage.

3) The remaining factor in equation (13) depends on the reliability-cost relationship for each subsystem and is determined separately for each. The character of the function Λ (MTBF) may be seen with the help of Figure 1. When the slope of the life-cycle-cost curve is zero, $\Lambda = 0$. The solution lies to the right of this point since one would not consciously pay more for less reliability. The function Λ (MTBF) is monotone increasing to the right of $\Lambda = 0$ if $\partial \Lambda / \partial \text{MTBF} > 0$ there. If Λ (MTBF) is monotone increasing, it possesses a unique inverse $\text{MTBF}(\Lambda)$ and, as we will see, the problem of the constrained minimum life-cycle cost has a straightforward and unique solution. To determine if Λ (MTBF) is monotone increasing, consider the derivative of equation (13):

$$\frac{\partial \Lambda}{\partial \text{MTBF}_{ij}} = \left(\frac{P_{H_{ij}} / T_i}{n_{ij} \tau_{ij}} \right) \text{MTBF}_{ij} \left(2 \frac{\partial \text{LCC}_i}{\partial \text{MTBF}_{ij}} + \text{MTBF}_{ij} \frac{\partial^2 \text{LCC}_i}{\partial \text{MTBF}_{ij}^2} \right)$$

Thus, $\partial \Lambda / \partial \text{MTBF}_{ij} > 0$ and possesses a unique inverse if both the slope and curvature of the function $\text{LCC}_i(\text{MTBF}_{ij})$ are positive, as is shown in Figure 1. Since the condition $\text{LCC}_i \rightarrow \infty$ as $\text{MTBF}_{ij} \rightarrow \infty$ likely holds, it is unlikely that $\partial^2 \text{LCC}_i / \partial \text{MTBF}_{ij}^2$ is ever negative, but even if it is, the curve $\Lambda(\text{MTBF}_{ij})$ is still monotone increasing if

$$\frac{\partial \text{LCC}_i}{\partial \text{MTBF}_{ij}} > \frac{\text{MTBF}_{ij}}{2} \left| \frac{\partial^2 \text{LCC}_i}{\partial \text{MTBF}_{ij}^2} \right|$$

Without more information on the functions $LCC(MTBF)$ it is not possible to prove rigorously that the above inequality always holds, but it seems highly plausible and will be assumed in the following analysis. Thus it will be assumed that $\Lambda(MTBF)$ possesses a unique inverse $MTBF(\Lambda)$ as shown in Figure 2, but to cover contingencies, it will be assumed that if $MTBF(\Lambda)$ is not unique the lowest value is to be used. Thus, as shown in Figure 2, if Λ is plotted as a function of $MTBF_{ij}$ for each failure class of each subsystem, the optimum value of each $MTBF_{ij}$ for minimization of system life-cycle cost can be found if the solution value of Λ for the entire system is found.

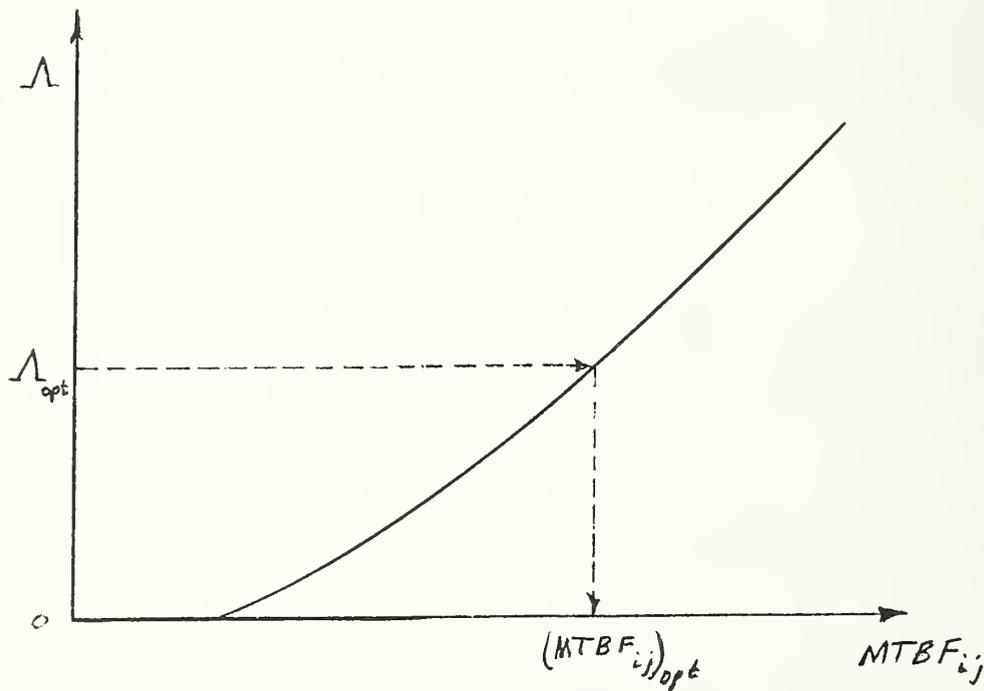


Figure 2 The Lagrangian Multiplier

The system value of Λ is found by satisfying the given constraint on system unavailability. Combining equations (2) and (5), we can now write

$$\epsilon(\Lambda) = \frac{1}{PH_{yr}} \sum_{i=1}^P r_i T_i \sum_{j=1}^{g_i} \frac{n_{ij} z_{ij}}{MTBF_{ij}(\Lambda)} \quad (14)$$

in which the functional dependence of $MTBF_{ij}$ and hence of ϵ on Λ is indicated. Thus, the solution proceeds as follows: For each failure mode of each subsystem, $\Lambda(MTBF_{ij})$ is found and plotted. The inverse functions $MTBF_{ij}(\Lambda)$ are found from curves such as Figure 2 and are used to compute the system curve $\epsilon(\Lambda)$ from equation (14). As indicated in Figure 3, ϵ is maximum at $\Lambda = 0$ in the domain $\Lambda \geq 0$ and is monotone decreasing as Λ increases. The later conclusion is a direct result of the facts 1) that all $MTBF_{ij}$ increase as Λ increases (see Figure 2); and (2) that $\epsilon(\Lambda)$ is a sum of reciprocals of the $MTBF_{ij}$ (see equation (14)).

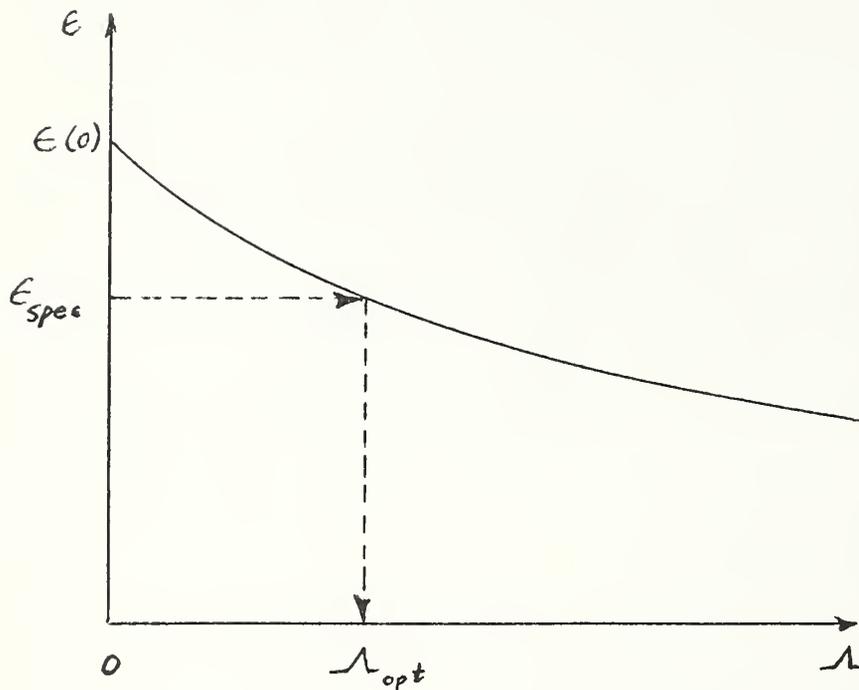


Figure 3 The System Constraint Function

If $\epsilon_{\text{spec}} \geq \epsilon(0)$, where ϵ_{spec} is the specified level of system unavailability, $\Lambda = 0$ and the solution is obtained by setting all $MTBF_{ij}$ such that all $\partial LCC_i / \partial MTBF_{ij} = 0$. In the usual case, however, $\epsilon_{\text{spec}} < \epsilon(0)$. Then, as indicated in Figure 3, the specified value of system unavailability yields a unique value $\Lambda = \Lambda_{\text{opt}}$. By entering the family of curves of Λ vs. $MTBF_{ij}$ with Λ_{opt} , a unique set of values of $(MTBF_{ij})_{\text{opt}}$ are found. These values minimize system life-cycle cost subject to the specified level of system unavailability.

If a given subsystem has only one class of failure there is a single set of curves like Figure 1 for that subsystem. If in a certain subsystem there is more than one class of failure, it is implied in the above minimization process that it is possible to derive the curve $LCC_i(MTBF_{ij})$ for one particular value of j while holding the $MTBF_{ij}$ for all other j constant. It is not clear that this would always be possible, but if not, the implication would appear to be that the definition of subsystems must be further broken down.

Certainly the curves of LCC vs. MTBF are not easily obtained in the early phases of a design. Preliminary reliability allocations are, however, necessary if a rational design is to ensue. Therefore, LCC vs. MTBF curves must be estimated in successively more detail by a three-step process:

- 1) Parametric analysis of costs as functions of various system parameters;
- 2) Refinement of costs by analogy with similar systems; and
- 3) Engineering cost analysis based on detailed designs.

Out of such analysis, increasing refinement of the functions $\partial LCC_i / \partial MTBF_{ij}$ can be made, but at increasing engineering cost. As indicated in the next section, a preliminary allocation of subsystem MTBF's can be made without life-cycle-cost data; then, in Section 8, it is shown how to obtain the next level of approximation based on preliminary values of $\partial LCC_i / \partial MTBF_{ij}$.

7. Approximate Solution to the Problem of Reliability Allocation

Equation (14) suggests the preliminary assumption

$$MTBF_{mn} = C n_{mn} \tau_{mn} \quad (15)$$

in which C is a constant and, to avoid confusion later, the dummy subscripts have been changed. This formula suggests that the MTBF's be allocated in proportion to the number of person-hours of delay due to a particular kind of failure. The constant C can be found by substituting equation (15) into equation (14). Thus

$$C = \frac{1}{E_{spec} PH_{yr}} \sum_{i=1}^p r_i T_i g_i \quad (16)$$

Substituting equation (16) into equation (15)

$$MTBF_{mn} = \frac{n_{mn} \tau_{mn}}{E_{spec}} \frac{N_v T_v}{PH_{yr}} \sum \quad (17)$$

in which

$$\Sigma = \sum_{i=1}^{i_{vs}} g_i + \frac{T_w}{T_v} \frac{1}{N_v} \sum_{i=p_{vs}+1}^p r_i g_i \quad (18)$$

is the sum of the total number of failure classes defined for vehicle subsystems plus a weighting factor times the number of failure classes in all wayside subsystems.

But n_{mn} can be expressed in the form

$$n_{mn} = \dot{n}_m \tau_{mn} \quad (19)$$

in which \dot{n}_m is the mean flow of people involved in a failure of subsystem m. Thus, equation (17) becomes

$$\boxed{MTBF_{mn} = \frac{\dot{n}_m \tau_{mn}^2}{\epsilon_{spec}} \frac{N_v T_v}{PH_{yr}} \Sigma} \quad (20)$$

The strong dependence of the required reliability on the time delay due to failure, τ_{mn} , is clearly evident from equation (20), thus indicating the importance of developing operational strategies in which failures can be cleared as quickly as possible. Since \dot{n}_m , N_v , and PH_{yr} are all proportional to patronage, the required MTBF is proportional to patronage, a conclusion which is intuitively reasonable. Also, equation (20) shows that, for a given patronage, if N_v increases due to use of smaller vehicles, $MTBF_{mn}$ increases unless by design changes τ_{mn} is decreased enough so that the product $N_v \tau_{mn}^2$ does not change. Thus, if $\tau_{mn} \propto N_v^{-1/2}$ the reliability requirements do not worsen in small-vehicle systems. If, in equation (18), the r_i do not increase in proportion to N_v , the dependence of $MTBF_{mn}$ on N_v is weakened.

8. Approximate Solution to the Problems of Minimization of Life-Cycle Cost and Reliability Allocation

Equation (20) allocates the reliability requirements in proportion to the number of person-hours of delay due to each type of failure, but makes no allowance for the possibility that the life-cycle costs of some subsystems may change more rapidly with MTBF than others. To account in as simple a way as possible for such variations, assume in equation (13) that, in the region of interest, ^{the} slopes of the curves of LCC_i vs. $MTBF_{ij}$ are constant, i.e., independent of $MTBF_{ij}$. Then equation (13) can be solved for $MTBF_{ij}$:

$$MTBF_{ij} = \left(\frac{n_{ij} \tau_{ij}}{LCC'_{ij}} \frac{T_i \lambda}{PH_{yr}} \right)^{1/2} \quad (21)$$

in which

$$LCC'_{ij} \equiv \frac{\partial LCC_i}{\partial MTBF_{ij}}$$

If equation (21) is substituted into equation (14), the result can be solved for $\Lambda^{1/2}$. Thus

$$\Lambda_{opt}^{1/2} = \frac{1}{E_{spec} PH_{yr}^{1/2}} \sum_{i=1}^I r_i T_i^{1/2} \sum_{j=1}^{q_i} (n_{ij} z_{ij} LCC'_{ij})^{1/2} \quad (22)$$

Substituting equation (22) into equation (21), using equation (19), and changing the dummy indicies i, j to m, n in equation (21), the MTBF's are seen to be allocated according to an equation identical to equation (20) if Σ is replaced by a new expression, Σ_{mn} . Thus

$$MTBF_{mn} = \frac{\dot{n}_m T_{mn}^2 N_v T_r \Sigma_{mn}}{E_{spec} PH_{yr}} \quad (23)$$

in which

$$\begin{aligned}
 \sum_{mn} = & \left(\frac{T_m}{T_v} \right)^{1/2} \sum_{i=1}^{P_{vs}} \left(\frac{\dot{n}_i}{\dot{n}_m} \right)^{1/2} \sum_{j=1}^{q_i} \frac{\tau_{ij}}{\tau_{mn}} \left(\frac{LCC'_{ij}}{LCC'_{mn}} \right)^{1/2} \\
 & + \frac{(T_m T_w)^{1/2}}{T_v} \sum_{i=p_{vs}+1}^P \frac{r_i}{N_v} \left(\frac{\dot{n}_i}{\dot{n}_m} \right)^{1/2} \sum_{j=1}^{q_i} \frac{\tau_{ij}}{\tau_{mn}} \left(\frac{LCC'_{ij}}{LCC'_{mn}} \right)^{1/2}
 \end{aligned} \tag{24}$$

Note that, if subscript m corresponds to a vehicle subsystem, $T_m = T_v$ and the second double summation, dependent on the wayside subsystems, is weighted by the ratio $(T_w/T_v)^{1/2}$, which is greater than one if $T_w > T_v$. If subscript m corresponds to a wayside subsystem, $T_m = T_w$ and $(T_w/T_v)^{1/2}$ factors out of equation (24). The second double sum is again weighted with respect to the first by the factor $(T_w/T_v)^{1/2}$. As indicated in Section 5, in most cases $(T_w/T_v)^{1/2} \leq (8760/3000)^{1/2} = 1.7 > 1$. Thus the systems in operation longer weigh more heavily in determining the reliability requirements, as should be the case. It is also seen from equation (24) that, since LCC'_{mn} is in the denominator, failure modes for which LCC increases more rapidly with MTBF are allocated a smaller MTBF, the correct direction to minimize life-cycle cost. Moreover, even without accounting for variations in LCC' , equation (24) is more realistic than equation (18) in that failure modes for which $n_{ij}\tau_{ij}$ is larger weigh more heavily in

determining the subsystem MTBF requirements. Also note from equations (23) and (24) that for a given set of values of $n_{ij}\tau_{ij}$, $i, j \neq m, n$, if $n_{mn}\tau_{mn}$ increases, $MTBF_{mn}$ increases in proportion to $(\dot{n}_m \tau_{mn}^2)^{\frac{1}{2}}$ instead of to $\dot{n}_m \tau_{mn}^2$ as is the case with the level of approximation of Section 7. Thus, holding all failure delay times constant except τ_{mn} , $MTBF_{mn}$ is proportional to τ_{mn} , not to τ_{mn}^2 as is the case with equation (20); however, if all of the τ_{mn} are reduced in the same proportion, $MTBF_{mn}$ still reduces in proportion to τ_{mn}^2 . If one of the τ_{ij} is large, all of the $MTBF_{mn}$ must suffer an increase in order to meet the specified system unavailability, ϵ_{spec} . This is clearly as it should be. Note from equation (23) that $MTBF_{mn}$ is proportional to the ratio \dot{n}_m / PH_{yr} , i.e., the ratio of flow rate in people per hour to person-hours of travel per year. This ratio is independent of patronage; however, N_v is proportional to patronage. Therefore, the MTBF requirements are proportional to patronage and to the number of vehicles in the system. If the reliability requirements are not to increase in smaller vehicle systems (larger N_v), it is necessary that the operational control system be designed so that the squares of the delay times due to failures decrease in the same proportion as N_v increases, i.e., that the product $N_v \tau_{mn}^2$ remain fixed. As the system size increased, PH_{yr} increases in proportion to N_v ; therefore, the reliability requirements do not change as the system grows. Equations (23) and (24) were derived under the assumption that the LCC' are constants. Even though this is not in general true, these equations are correct if the correct LCC' are substituted. The correct LCC' can be found by iteration with equations (23) and (24), or exactly by means of the procedure described in Section 6.

9. Summary

A method is developed for allocation of the reliability requirements of the subsystems of an automated transit system in such a way that life-cycle cost is minimized. Besides a complete classification of the subsystems and their failure modes, the method requires knowledge of (1) the yearly number of hours of operation of the vehicle-bourne and wayside equipment, (2) the mean number of person-hours of delay due to each failure (failure effects analysis), and (3) the slopes of the curves of subsystem life-cycle cost vs. MTBF.

The exact solution is given by equations (13) and (14); however, using it the numerical solution is graphical. An analytic approximation, adequate if the variation in the slopes of the life-cycle-cost curves are small, is given by equation (23) together with equation (24). The later solution has the additional advantage of providing a great deal of insight into the behavior of MTBF requirements with various parameters. It shows that the MTBF requirements are:

- 1) Proportional to patronage;
- 2) Independent of system size;
- 3) Proportional to the square of the time delays due to failure; and
- 4) Linearly increasing with the number of vehicles. Thus, if, with a given patronage, the vehicle size is reduced so that N_v increases, τ_{mn}^2 must be caused to decrease in the same proportion if the MTBF requirements are not to worsen. Thus, more sophisticated control systems are required in small-vehicle systems than in large-vehicle systems.

(End of Paper 1 Presentation)

The next speaker is Dr. William Womack from the Otis Elevator Company in Denver. Dr. Womack has a BS Degree in Mechanical Engineering from Louisiana State Polytechnic Institute, an MS Degree in Applied Mechanics from Louisiana Tech, and a PhD Degree from the University of Oklahoma. He's been a Mission Analyst for the U.S. Air Force and Dual Mode Program Manager at Otis, and is now Chief of System Engineering at Otis. His talk is titled "An Approach to Automated Guideway System Dependability Analysis."

PANEL 3
PAPER 2

AN APPROACH TO AUTOMATED GUIDEWAY
SYSTEM DEPENDABILITY ANALYSIS

W.C. WOMACK
J.F. DEXTER
R.L. WEST

AN APPROACH TO AUTOMATED GUIDEWAY SYSTEM DEPENDABILITY ANALYSIS

W.C. Womack
J.F. Dexter
R.L. West

Abstract

Traditional approaches to reliability analysis were developed for systems having different usage requirements than automated transit systems. The concept of service dependability presented herein is an extension of traditional reliability approaches and enables analysis of system operational characteristics in terms of the frequency and duration of delays which will be experienced by the typical user of automated transit systems.

1. INTRODUCTION

To the individual user of any public transportation system, one of the most visible operational characteristics is the capability of the system to deliver him to his destination on schedule. The design of new systems must, therefore, include a meaningful analysis of the ability of the system to perform dependably. The traditional approaches of reliability and availability do not provide a measure of a system's capability to perform dependably in terms which relate to the inconvenience experienced by the individual commuter as a result of system element failures--hence, the need for an analysis technique more directly suited to automated transit systems' needs.

The analysis technique described herein presents a method of assessing a systems' performance in a manner directly relatable to the individual passenger. This measure of performance is called SERVICE DEPENDABILITY.

Service Dependability is specified in terms of the frequency and duration of delays which will be experienced by the "average" system user and, thus, in terms much more readily communicated to prospective purchasers and users of the system than the traditional availability percentages.

The analysis technique described herein has not been validated through hardware experience; however, adequate work has been performed using the technique to indicate that it is worthy of further consideration.

The concept of service dependability was developed by OTIS in cooperation with the Urban Mass Transportation Administration (UMTA) of the U. S. Department of Transportation (DOT) during performance of Phase I of the UMTA/DOT High Performance Personal Rapid Transit Program.

2. TRADITIONAL RELIABILITY APPROACHES VERSUS SERVICE DEPENDABILITY ANALYSIS

Traditional reliability analyses predict the probability that a given system will perform without failures for a fixed period of time. The mathematical techniques involved have been developed to a high degree in the aerospace industry to predict the probability of success of "one-shot" missions having clearly defined durations and objectives.

Availability analyses combine reliability assessment with a measure of the maintainability of the system to predict the amount of time that a system will be inoperative over a given period of operating time.

Both of these analysis techniques provide a measure of the system's ability to provide dependable service, but they do not do so in terms which can easily be related to the individual user of the system.

The service dependability analysis combines traditional reliability and availability analyses with an assessment of the user's exposure to the system and the system's operating characteristics to provide a probabilistic measure of the frequency and duration of the delays to which the user will be subjected. It is thus a measure of the system's effectiveness as viewed by the individual user.

3. SERVICE DEPENDABILITY ANALYSIS TECHNIQUES

The service dependability analysis involves two related but separate analyses, allocation and prediction. The specified system-level dependability requirements are allocated through the system to the component/subsystem level to establish design reliability requirements.

In addition, reliability predictions are made at the subsystem/component level and are combined through the system to achieve a predicted system-level dependability. The predicted and allocated reliabilities may then be compared at all levels to detect areas in which the allocations or predictions must be adjusted to achieve a system having adequate dependability at reasonable cost.

The allocation process will be discussed first, followed by prediction in the following sections.

3.1 Service Dependability Requirements - Service dependability requirements are specified in two forms: the service dependability curve and the cumulative annual additional travel time. The service dependability curve is a plot of the permitted frequency of occurrence of delay (measured in terms of user trips per occurrence) versus the impact of the delay (measured in terms of additional trip time experienced by the user). The curve simply suggests that a user will accept a relatively greater number of short delays than long delays. These delays are experienced by the "typical user" with a "typical service profile."

The service dependability curve presented in Figure 1* is provided to facilitate this discussion. The specific values or curve shape may not provide the best measure of user acceptance of delays. This paper will not attempt to develop the specific values for use

*Refer to end of paper for figures.

on this curve but will only discuss how the curve is used in specification or service dependability.

The service dependability curve defines the number of trips between delays (TBD) that a passenger will judge acceptable as a function of the duration of each delay.

The delay durations selected are a function of the maintainability of the system being analyzed and the restorative actions available to the system operator. For the purpose of this discussion, three distinct delay time classes will be used: of 3-minute, 24-minute, and 45-minute duration. From the service dependability curve, the following can be determined:

<u>Class</u>	<u>Length of Delay</u>	<u>Frequency of Occurrence of Delay</u>
A	3 Minutes	1 per 20 Trips
B	24 Minutes	1 per 160 Trips
C	45 Minutes	1 per 500 Trips

It is now necessary to define the activity of the "average" commuter upon which the analysis will be based. This depends on the specifics of the systems being analyzed. For this analysis, a peak-hour commuter will be assumed who makes 10 trips per week, 50 weeks per year.

The service dependability curve thus indicates that he will encounter one 3-minute delay every 2 weeks (20 trips), 1 24-minute delay during 4 months (160 trips), and 1 45-minute delay every year (500 trips). -This enables calculation of the cumulative annual additional travel time as follows:

<u>Class</u>	<u>Length of Delay (Maximum)</u>	<u>Annual Number of Delays</u>	<u>Maximum Class-Related Delay Time</u>
A	3 Minutes	25	75 Minutes
B	24 Minutes	3.125	75 Minutes
C	45 Minutes	1	45 Minutes
TOTAL			195 Minutes

The discussion thus far has developed the philosophy behind specification of service dependability requirements, but what can be done if the system to be analyzed is specified in terms of conventional availability.

Relation to Availability - As will be developed later, the exposure of the average commuter to the system is 20 minutes per trip, or 10,000 minutes per year. If the specified availability* for the system should happen to be 98%, the allowable total delay per year is 200 minutes. This is, in fact, the cumulative annual additional

*Availability is defined as $\frac{\text{Operating Time}}{\text{Operating Time} + \text{Down Time}}$ and is expressed as percent.

travel time. The restoration time data and service dependability curve can be used to translate this time to service dependability requirements by reversing the process used to determine the cumulative annual additional travel time from the service dependability curve.

3.2 Traditional Reliability/Service Dependability Relationship - The system-level service dependability requirements have been developed in the preceding section. These requirements must be translated into traditional reliability requirements at the component/subsystem level in order to provide design guidance and enable measurement of the system's probability of fulfilling the operational requirements. The capability to make the required translation depends on the concept of user exposure time and service profile. The frequency at which a user experiences delays is dependent on the failure rate of the system and the time he is exposed to the system (or exposure time, ET). The failure rate of the system is expressed in terms of the conventional reliability measure--"mean time between failures" (MTBF). The number of trips between delays (TBD) can be expressed as follows:

$$TBD = \frac{MTBF}{ET} \text{ which becomes } MTBF = (TBD) (ET)$$

Thus, if the user's exposure time is known, the service dependability requirements can be translated into conventional MTBF terms.

3.3 User Exposure Time - User exposure time to the system is determined from the user's service profile. The user's entry into the system occurs at the point in time when he expects the system to respond to his transportation needs, whether in response to a service request or in response to scheduled service expectations. After system exit, the user no longer expects the system to respond.

For the purposes of the analysis, the average commuter will be assumed to enter the station and request service, board a vehicle and proceed to an intermediate station, and then proceed to his destination. The time involved will be assumed to be as follows:

- In-Station User Wait 5 minutes maximum
- Intermediate Station Vehicle Dwell Time 30 seconds maximum
- Distance Between Initial and Intermediate Stations 3.67 miles
- Distance Between Intermediate and Final Station 3.59 miles
- Typical User Trip Length 7.26 miles
- Average Speed 30 miles per hour.

Using these parameters and the user's service profile, the user exposure time to the system is determined to be 20.0 minutes.

3.4 System-Level Mean Time Between Failures (MTBF) - With system exposure time defined and the user's delay frequency determined from the service dependability curve, the allocated system MTBF can be calculated. The system MTBF's for the sample system are:

<u>Class</u>	<u>Length of Delay</u>	<u>MTBF (System)</u>
A	3 Minutes	6.67 Hours (1 failure per 20 trips @ 20 minutes per trip)
B	24 Minutes	53.33 Hours (1 failure per 160 trips @ 20 minutes per trip)
C	45 Minutes	166.67 Hours (1 failure per 500 trips @ 20 minutes per trip)

3.5 Number of Systems Affecting User - Now that the system-level MTBF requirements have been determined, the scope of the system over which these times are distributed must be defined. In order to achieve manageable numbers of system elements affecting the trip, the system must be structured so that the effect of failures can be localized rather than bringing the entire system to a screeching halt. This enables definition of a finite number of system elements whose failure will delay the commuter's trip and depends upon allowing vehicle bunching upstream of the failure and the existence of alternate routes around the failure site. Since the number of system elements to which the commuter is exposed decreases during the trip, the worst-case number of elements will be averaged to determine the number affecting his trip.

Failure modes which cause a given vehicle to be stopped on the guideway for 24 minutes affect the progress of a greater number of upstream vehicles than failures which result in a 3-minute stoppage; however, the analysis technique is similar in all cases.

It will be assumed that the vehicles operate at headways exceeding the minimum-safe headway. Therefore, some compression between vehicles is possible. If a failure occurs adequately far downstream from our commuter's vehicle that the system is restored to normal service prior to consumption of all available compression, no delay is incurred. In the case of the 3-minute failure, a string of vehicles adequately long to provide 3 minutes of compression is the maximum number which can influence the commuter's trip. The number of vehicles in this string is calculated as follows:

- Available Compression
 - Operating Headway 5.43 seconds
 - Minimum-Safe Headway -3.30 seconds
 - Available Compression 2.13 seconds

- Number of Vehicles

$$3 \text{ min.} \times \frac{60 \text{ sec.}}{\text{min.}} \times \frac{1 \text{ veh.}}{2.13 \text{ sec.}} = 84.5 \text{ vehicles.}$$

This is the maximum number of vehicles which can affect the assumed commuter trip. A shorter trip length of alternate path (branch) along the way would reduce this number. As the commuter's vehicle approaches the destination station, fewer leading vehicles can influence progress; since less compression time is required to allow reaching the station. The number influencing the commuter's vehicle begins to decrease when the lead vehicle in the string which provides three minutes of compression reaches the destination station, and decreases linearly to zero when the commuter's vehicle reaches the destination station.

The time at which the lead vehicle reaches the destination station can be calculated as follows:

The length of the string of vehicles yielding three minutes of compression is--

$$84.5 \text{ vehicles} \times \frac{5.43\text{-second headway}}{\text{vehicle}} \times \frac{44 \text{ feet}}{\text{second}} \times \frac{1 \text{ mile}}{5,280 \text{ ft}} = 3.82 \text{ miles}$$

The trip time to traverse 3.82 miles at 30 mph is--

$$3.82 \text{ miles} \times \frac{5,280 \text{ ft}}{\text{mile}} \times \frac{1 \text{ sec}}{44 \text{ ft}} \times \frac{1 \text{ min}}{60 \text{ sec}} = 7.64 \text{ minutes}$$

Thus, when the commuter's vehicle is 7.64 minutes from the destination station, the number of vehicles which can influence his progress begins to decrease.

Based on this analysis, the curve in Figure 2 can be plotted.

The commuter is exposed to the full string of 84.5 vehicles for only a portion of his trip. The average number of vehicles to which he is exposed is--

$$\text{Avg Number of Vehicles} = \frac{\text{Area of Curve}}{\text{Time of Exposure}}$$

$$N_{V \text{ avg}} = 68.35 \text{ Vehicles.}$$

3.5.2 Twenty-Four and Forty-Five-Minute Cases - Since the commuter is never more than 20 minutes from his destination, the maximum required compression is 20 minutes in all cases in which the time to restore service exceeds 20 minutes. Using the same analysis utilized in the 3-minute case, the following results:

Maximum Number of Vehicles	562 vehicles
Length of String	25.43 miles
Average Number of Vehicles	281 vehicles.

It is probable that no urban system will be built in which no alternate paths are available in 25 miles of guideway. Further, the number of vehicles involved necessitates reliabilities which are not attainable. The following alternate analysis is used, based on assumed alternate paths at 7.26-mile spacing. This spacing was chosen to coincide with the base trip length.

The string of vehicles which can affect progress using alternate paths is only as long as the link between the commuter's vehicle and the branch point, since failures beyond the branch will cause rerouting rather than clogging.

A string of vehicles 7.26 miles long is composed of the following number of vehicles:

$$7.26 \text{ miles} \times \frac{5,280 \text{ ft}}{\text{mile}} \times \frac{\text{sec}}{44 \text{ ft}} \times \frac{\text{vehicles}}{5.43 \text{ sec}} = 160.44.$$

The number of vehicles affecting progress decreases linearly from origin to destination. The average number of vehicles affecting progress is then 80.22 vehicles.

3.5.3 Automatic Controls Quantity Analysis - Since the wayside automatic control system is not composed of discrete modules as in the vehicle's case, definition of quantity is more difficult. For the purpose of the analysis, the quantity will be taken to be the number of local controller segments involved. Using the alternate paths approach, all affecting local controller elements reside in the 7.26 miles of guideway over which the commuter travels. The local controller segments will be assumed to span approximately one mile each; therefore, approximately seven local controllers are involved. The number of local controllers affecting progress decreases linearly during the trip, so that the average number of local controllers is 3.5.

3.5.4 Facilities Quantity Analysis - Following the same logic as used in the automatic controls quantity analysis, the number of facilities involved will be taken to be the number of stations involved. Since three stations are involved, and the intermediate station is located approximately midway between the origin and destination stations, the average number of facilities affecting the commuter's progress is 1.5.

3.5.5 Number of System Elements Affecting Progress - The subsystems affecting the commuter's progress are summarized as follows:

Subsystem	Failure Class		
	A	B	C
Vehicles	68.35	80.22	80.22
Command and Control	3.5	3.5	3.5
Facilities	1.5	1.5	1.5

3.6 System Mean Time Between Failure (MTBF) Allocation - The system-level MTBF's and equipment quantities have now been determined and may be allocated and apportioned to lower subsystems. For the purpose of this allocation, the sample system is divided into three major systems: 1) Vehicle, 2) Automatic Control, and 3) Facilities. Assuming constant failure rate systems, the MTBF's can be apportioned in the following manner:

$$\frac{1}{\text{MTBF}_{\text{SYSTEM}}} = (X) \frac{N_V}{\text{MTBF}_{\text{VEHICLE}}} + (Y) \frac{N_{\text{C\&C}}}{\text{MTBF}_{\text{C\&C}}} + (Z) \frac{N_{\text{FAC.}}}{\text{MTBF}_{\text{FAC.}}}$$

where N_V = Number of vehicles affecting user

$N_{\text{C\&C}}$ = Number of automatic control systems affecting user

$N_{\text{FAC.}}$ = Number of facilities affecting user

X,Y,Z = Proportion of MTBF apportioned to each system based on the number of failure modes in each system.

The MTBF's are then allocated to the component/subsystem level using conventional reliability fault tree analysis. For the sample system, the following allocations result:

<u>Failure Class</u>	<u>Vehicle</u>	<u>Automatic Control</u>	<u>Facility</u>
A	760	78	100
B	7,000	620	800
C	22,000	1,900	2,500

Analysis of the Otis system elements against these subsystem MTBF allocations indicate that the Class A failure mode requirements are achievable using currently available equipment implemented in a "single thread" manner. The Class B and C failure mode requirements are achievable using currently available equipment, provided adequate design attention is given to the following:

- Redundant implementation of critical subsystems
- Fault monitoring to enable detection of failed redundant elements

- Implementation of "fail operational" management strategies to minimize impact of failures
- Maintainability consideration in the interest of minimizing fault correction time.

3.7 Service Dependability Predictions - Reliability estimates made at the component/subsystem level are combined using the same system math model used for allocation. Conventional reliability techniques are used to account for element usage including redundancies, maintenance actions, etc. A comparison of the allocated and predicted reliability values is used to reveal problem areas such as faulty allocation of the available MTBF's among the top-level subsystems or areas of design deficiencies which must be improved via redundancy or alternate component selection.

4. SUMMARY

The technique described herein enables the specification of system operating dependability in terms of the average commuter's frequency and duration of delay. It preserves the desirable aspects of conventional reliability in enabling a system-wide assessment of low-level reliability requirements-- while expressing the top-level requirements in a more usable manner.

This approach appears to be logically sound; however, it must be noted that no hardware validation of the technique has been performed and, until validated by hardware experience, must be considered postulative.

BIOGRAPHY

John F. Dexter received a BSME degree from General Motors Institute in 1967. He was employed by the Chevrolet Engineering Center in Warren, Michigan, from 1963 through 1967 as a Cooperative Student, and from 1967 through 1969 as a Development Engineer in the Engine Test Laboratories. He has been employed by Transportation Technology Division, Otis Elevator Company, since 1969 and has contributed to the development of that Division's transit systems including participation in the TRANSP0 '72 Demonstration.

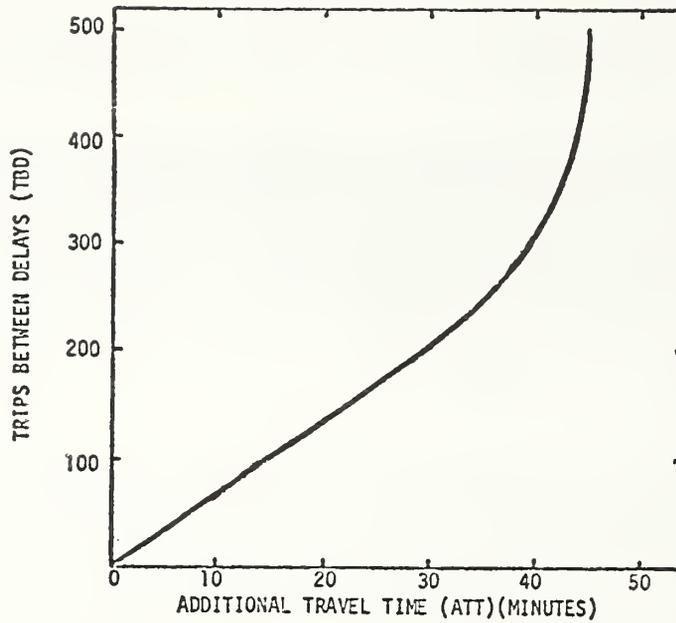
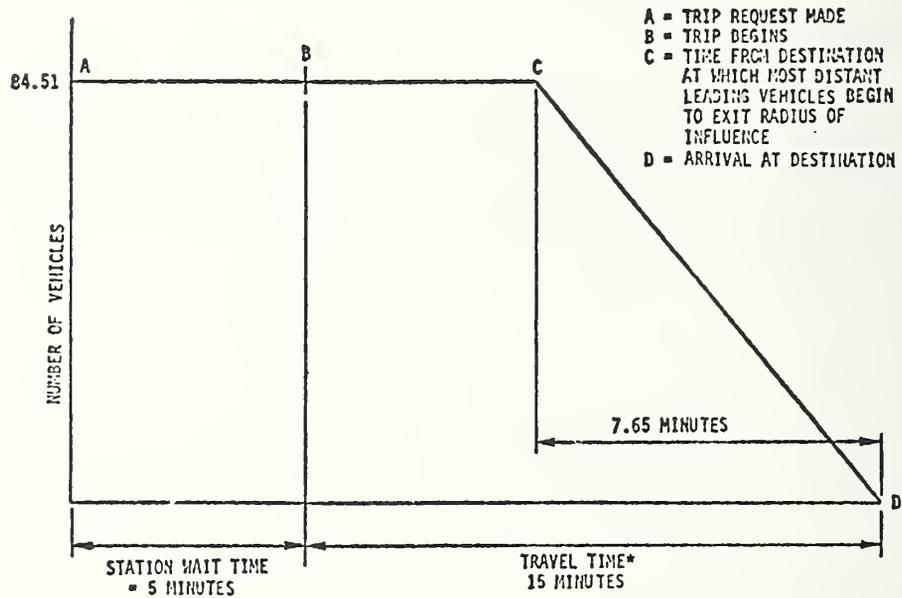


FIGURE 1. SERVICE DEPENDABILITY CURVE



*TRAVEL TIME IS BASED ON 30 MPH AVERAGE SPEED, AND INCLUDES A 30 SECOND INTER-MEDIATE STATION DWELL.

$$N_v = \frac{\text{AREA OF GRAPH}}{\text{EXPOSURE TIME}} = 68.35 \text{ VEHICLES}$$

FIGURE 2. SYSTEM EXPOSURE TIME/NUMBER OF SYSTEMS AFFECTING USER, CLASS A FAILURE CASE

(End of Paper 2 Presentation)

Dr. Anderson

Thank you very much, Bill. Now we're going to get into some papers that get into probability theory. The first is by Lee Tucker. He is currently the program manager of the Phase 2A AGRT Urban Deployability Study, and he came from the program at Calspan. He worked on the same program at Calspan, where he performed failure modes and effects analysis and availability analysis. The title of his talk is "Availability Analysis for Automated Guideway Transit Systems."

PANEL 3
PAPER 3

AVAILABILITY ANALYSIS FOR
AUTOMATED GUIDEWAY TRANSIT
SYSTEMS

H. L. TUCKER AND I. J. SACKS

ANAILABILITY ANALYSIS
FOR
AUTOMATED GUIDEWAY TRANSIT SYSTEMS

H. L. TUCKER

I. J. SACKS

ABSTRACT

An analytic approach has been developed in order to allow the rapid and efficient computation of availability estimates for automated guideway transit systems. The approach employs conditional probability formulations which represent vehicle, guideway and station/command control system reliability of any network. For the purposes of demonstration, a typical network has been assumed and availability estimates have been computed. A simulation package which generates the required estimates has been developed, and is also described.

1. AVAILABILITY ANALYSIS

1.1 OVERVIEW OF APPROACH

The availability analysis is based on the failure analysis, and takes two specific conditions into account (Figure 1). These include:

- A. A passenger (O/D pair) requests a trip and there is a route available. When enroute, the passenger may experience a failure.
- B. A passenger requests a trip for which all of the routes are unavailable, and the passenger must wait for the failure to clear.

The first case is handled by the method of "operational probabilities" described below. The second case, B, is also discussed below. Some assumptions have been made to allow a tractable analytic solution. These assumptions include:

1. The passenger (vehicle) will be delayed an amount of time equal to the recovery time of the failed element. That is, dynamic rerouting is not considered.
2. Multiple failures do not occur with a great enough frequency to affect the solution.

These cases are combined into an overall system availability graph described below.

Case A

The approach to be taken in generating the dependability diagram for a trip rerouted or not taken due to a prior failure is based on the combination of the "operational probability" of elements. These operational probabilities are the percentage of the time that a specific system element, such as a link, is available to the system. They are based on the element failure distributions and repair distributions. The operational probabilities will be discussed later in this section. These "operational probabilities" are combined into an overall probability that a specific route for a specific O/D pair is operational.

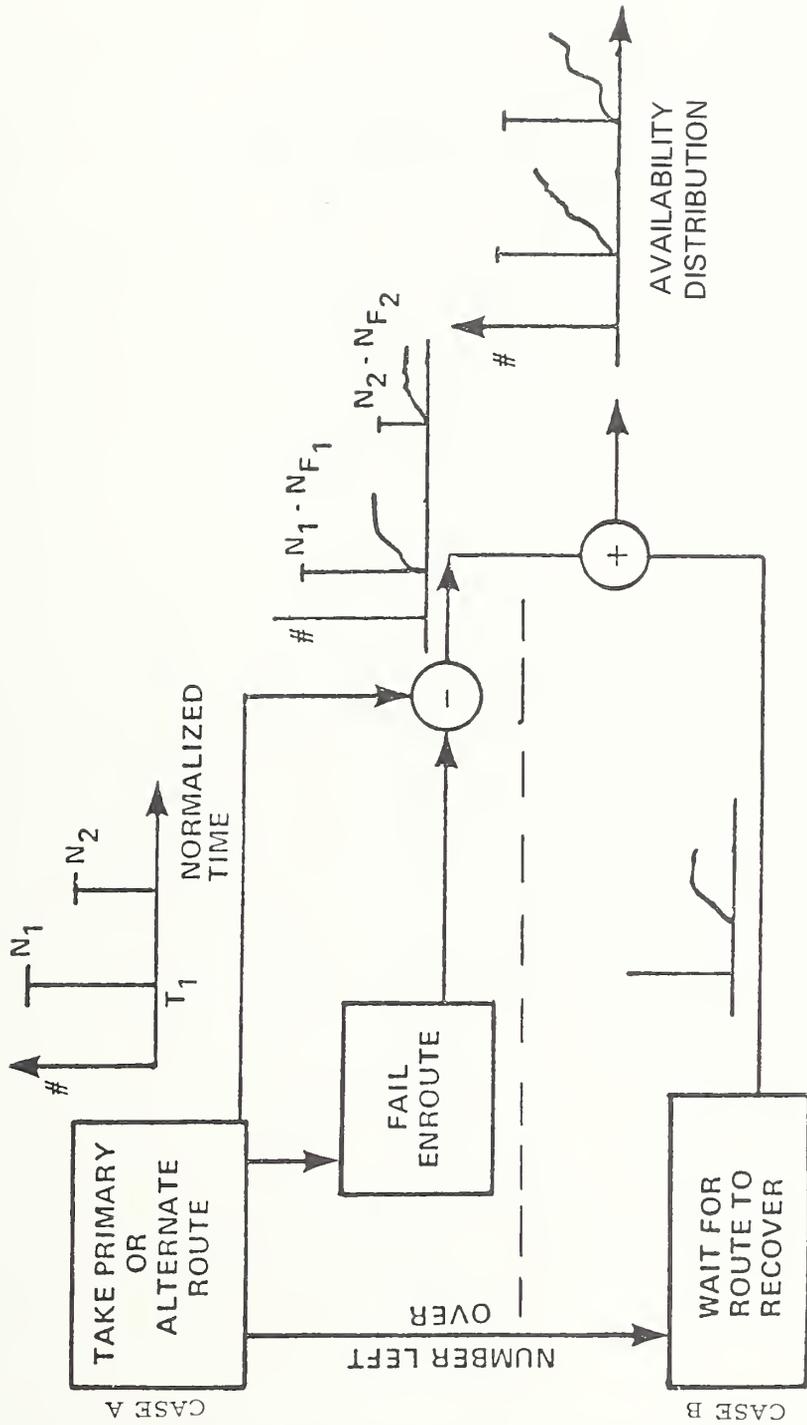


FIGURE 1. AVAILABILITY CASES

The probability of a route being available for use is given by

$$P(R_\ell)_{O/D_k} = P(\ell_\ell) \dots P(\ell_m) \cdot P(M_x) \dots P(M_y) \cdot P(S_o) \cdot P(S_D) \quad (1)$$

where $P(R_\ell)_{O/D_k}$ is the probability that route ℓ for O/D pair k is operational. This measure is called "availability."¹

$P(\ell_\ell)$ is the probability that link ℓ is operational.

$P(M_x)$ is the probability that merge x is operational.

$P(S)$ is the probability that the origin (or destination) station is operational when needed.

The specific route is a series of links and merges which are dependent on the topology of the network, the link loads, and the operational probability of the route. The routing algorithm in the AGT system will select the "best" route for each party, based on the above and some "cost" function such as minimum time. The analytic failure analysis assumes that the primary route and alternate routes for any O/D have been calculated based on some routing rule, and that the alternate route will be used if and only if the primary is not available due to a failure.

The method of determining a failure is indicated in the flow diagram analysis in Figure 2. The first step in the analysis is the determination of the nominal steady-state link flows on all links of the network. This assumes that all links are always operational, and that all vehicles will take their primary routes. The calculation of the link flows is based on the number of vehicles from each O/D pair which use the specific link, the link velocity, and the link length. The time spent on the link is also calculated by the use of the link velocity and link length. Using these link flows (number of vehicles on the link), a set of "operational probabilities" for each

¹Probabilistic Reliability: An Engineering Approach, Shooman, M.L., McGraw Hill, 1968.

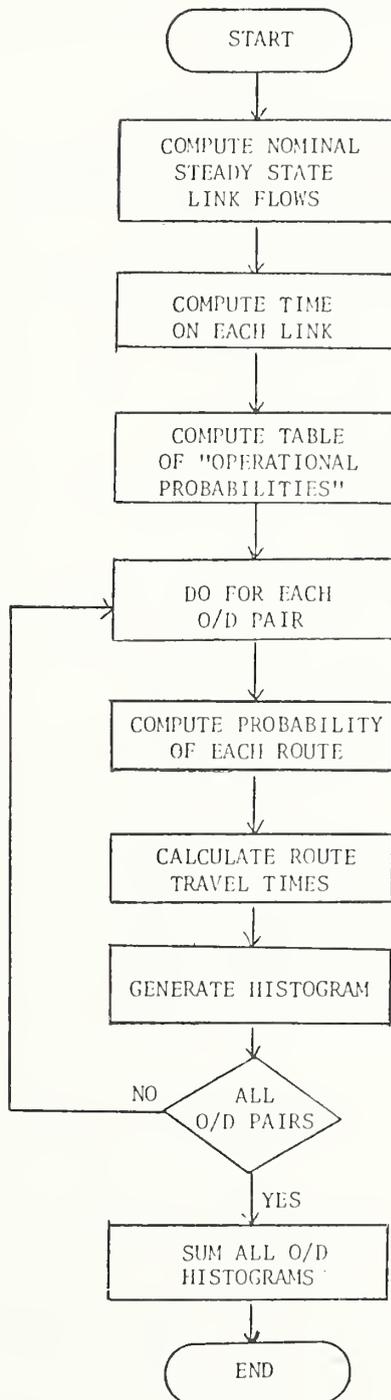


FIGURE 2. ANALYTIC FAILURE ANALYSIS FLOW

link is computed. This "operational probability" is the probability that the link is not closed, and is given for any link, ℓ , by

$$P(\ell_\ell) = 1 - \overline{P(\ell_1)} \quad (2)$$

where $\overline{P(\ell_1)}$ is the probability of the link being in failure. Link failure is assumed at this link to be due to two possible causes: guideway failure, or vehicle failure. The probability of a link being in failure then is given by

$$\overline{P(\ell_\ell)} = P(G) \overline{P(V_N)} \cdot P(V_N) \overline{P(G)} + \overline{P(V_N)} \overline{P(G)} \quad (3)$$

where $P(G)$ is the probability of the guideway being operational
 $\overline{P(G)}$ is the probability of the guideway being not operational
 $P(V_N)$ is the probability of all N vehicles on the link being operational
and $\overline{P(V_N)}$ is the probability of any one of the N vehicles being inoperative.

These probabilities can be calculated from the failure and recovery distributions for guideways and vehicles. The procedure for finding operational probabilities for each single element with repair is described in the next section.

Referring back to Figure 1, the element operational probabilities are then combined via equations (3), (2), and (1) into an overall route operational probability. This is done for each O/D pair and each possible (precomputed) route between O/D pairs. A histogram is then generated for the primary and alternate routes from the O/D pairs by the following process:

The probability of taking each route is computed. The probability of taking the first route is $P(R_1) \cdot [E_q(1)]$. The probability of taking the second route is

$$P(R_{02}) = \overline{P(R_1)} \quad P(R_2) = [1 - P(R_1)] \cdot P(R_2) \quad (4)$$

where $P(R_2)$ is the operational probability of the second route. The probability of using the third route is

$$P(R_{03}) = [1 - P(R_1)] [1 - P(R_2)] P(R_3) \quad (5)$$

where $P(R_3)$ is the operational probability of the 3rd route. For the n^{th} alternate route, the probability of using this route is

$$P(R_{on}) = \prod_{i=1}^{n-1} [1 - P(R_i)] P(R_n)$$

These probabilities are then weighted by the mean numbers of entries in the appropriate position in the O/D matrix and plotted against the travel time for their respective routes. The travel times are computed by using the link sequence and link velocities. This histogram is shown in Figure 3.

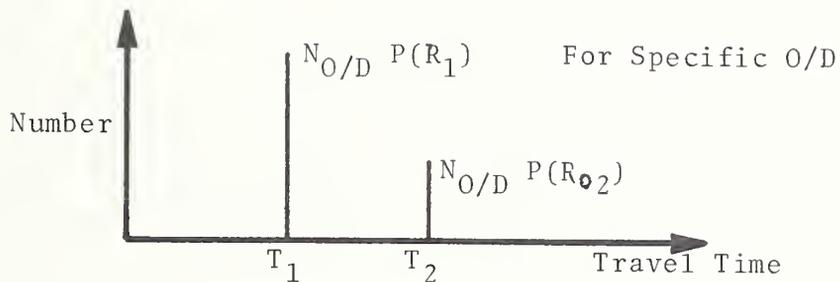


FIGURE 3. SINGLE O/D PAIR HISTOGRAM

This leaves a certain percentage of trips which will not take any route. This percentage is

$$P(R_{00}) = \prod_{i=1}^N [1 - P(R_i)] \cdot 100 \quad (6)$$

and is the percentage which is used in Case B.

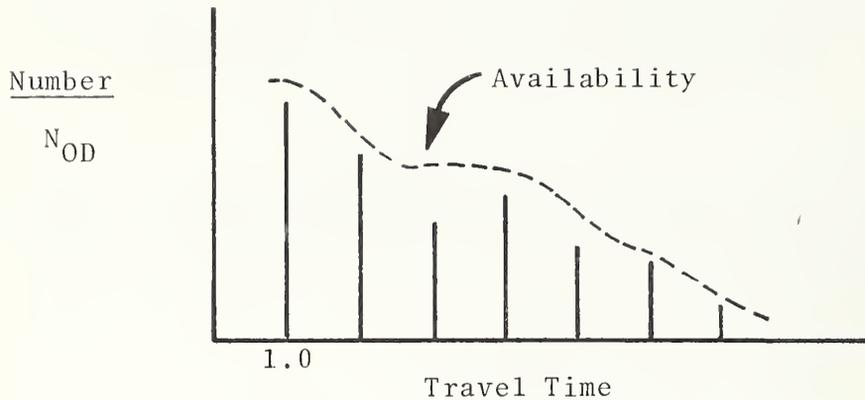


FIGURE 4. HISTOGRAM - CASE A

The analysis so far has not included the increase in travel times due to passengers delayed while enroute. The histogram shown in Figure 4 implies that all passengers who are routed reach their destination in the nominal travel time for that route. In reality, some of these trips will be delayed due to failures. This portion of this section discusses the analysis for these cases.

The probability of encountering a failure while enroute is given by the combinations of probabilities shown in Equation 7. This equation includes only single element failures, and ignores multiple failures (due to their low incidence). The probability of a failure on the trip due to a single element failure is then

$$P_F = \sum_{\ell=1}^k P_{\ell} \prod_{\substack{n=\ell \\ n \neq \ell}}^k (1 - P_n) \quad (7)$$

where P_{ℓ} is the probability of an element failing and $1 - P_n$ is the probability of an element not failing. These failure probabilities are a function of the type of element, vehicle, link, merge, or station and the exposure time to each of these elements. The exposure times to various elements are listed below.

<u>Element</u>	<u>Exposure Time</u>
Vehicle	Travel Time
Link	Time to Traverse Link
Merge	Time to Traverse Merge

In addition, certain elements will have failure probabilities influenced by vehicle flow rates. These elements include merges and links. The failure probability for a link is given by

$$P_L = P_F(G) \overline{P_F(V_N)} + \overline{P_F(G)} P_F(V_N) + \overline{P_F(G)} \overline{P_F(V_N)} \quad (8)$$

where $P_F(G)$ is the probability of the guideway failing

$P_F(V_N)$ is the probability of any of the N vehicles on the link failing

$\overline{P_F(V_N)}$ is the probability of no vehicle failing

$\overline{P_F(G)}$ is the probability of the guideway not failing

The guideway failure distribution is taken to be exponential:

$$P_F(G) = 1 - e^{-\lambda_G \Delta T} \quad (9)$$

where ΔT is the exposure time to the guideway and equals the guideway length divided by the vehicle velocity.

The vehicle failure distribution is also taken to be exponential:

$$P_F(V) = 1 - e^{-\lambda_V \Delta T} \quad (10)$$

where ΔT is the same as above. For N vehicles on the guideway, the probability of any one vehicle failing is

$$P_F(V_N) = 1 - (1 - P_F(V))^N \quad (11)$$

These equations can then be combined into a failure probability for each link.

A failure probability for the enroute vehicles on each route is generated by use of the above equations and equation (7). The number of passengers who will experience a failure on this route is then

$$N_F = N_{O/D} \cdot P(R_{O\ell}) \cdot P_F \quad (12)$$

where $N_{O/D}$ is the number of passengers in the O/D matrix

$P(R_{O\ell})$ is the probability of taking this route, and P_F is defined in equation (7). The values plotted on each of the histograms for each O/D pair must be reduced by the appropriate N_F for each of the routes. These enroute delayed passengers will have a trip determined by their nominal route time plus the recovery time. The recovery time density function for these parties is composed of the weighted recovery time from failures in each element of the route. This is shown in equation (13).

$$\rho_R(t) = \frac{\sum_{n=1}^k P_n \rho_{R_n}(t)}{\sum_{n=1}^k P_n} \quad (13)$$

where P_n is the failure probability for element n of the route

$\rho_{R_n}(t)$ is the recovery density function for element n .

This weighted distribution is then weighted by N_F and referenced to the corresponding route time and added to the individual O/D histogram. This is shown in Figure 5.

CASE B. Passengers Who Must Wait for Recovery

The number of passengers who must wait for recovery is given by equation (6). The travel time for these passengers is computed from the recovery distributions for each element of the primary route. It is assumed for this analysis that the AGT system will use this route in this case. These failure probabilities

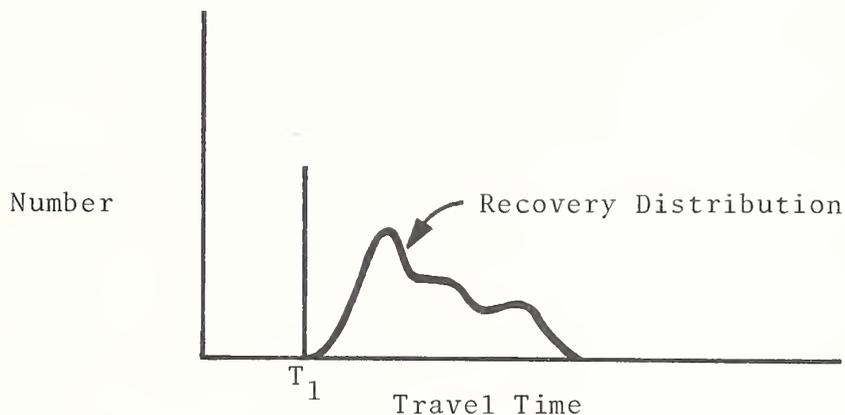


FIGURE 5. SINGLE O/D PAIR HISTOGRAM WITH RECOVERY

of each element can be used to weight the recovery distributions for each element, assuming no simultaneous failures to generate a composite recovery distribution. This is shown in equation (14) for any route.

$$\rho_R(t) = \sum_{\ell=1}^M \frac{P_F(E_R) \cdot \rho_r(E_\ell)}{\sum_{\ell=1}^M P_F(E_R)} \quad (14)$$

$$\rho_{R_0}(t) = P(R_{O/D}) \cdot \rho_R(t)$$

This $\rho_R(t)$ adds a distribution to the histogram referenced at the time of the primary route and normalized by the number in the O/D matrix, as was previously shown in Figure 5.

The times on the abscissa of the single O/D histograms are then normalized by the primary travel time. This process is repeated for each O/D pair, and the results are then summed into a system level availability histogram in which the ordinate variable is normalized by the total number of trips (sum of $N_{O/D}$ for all O/D's). See Figure 6.

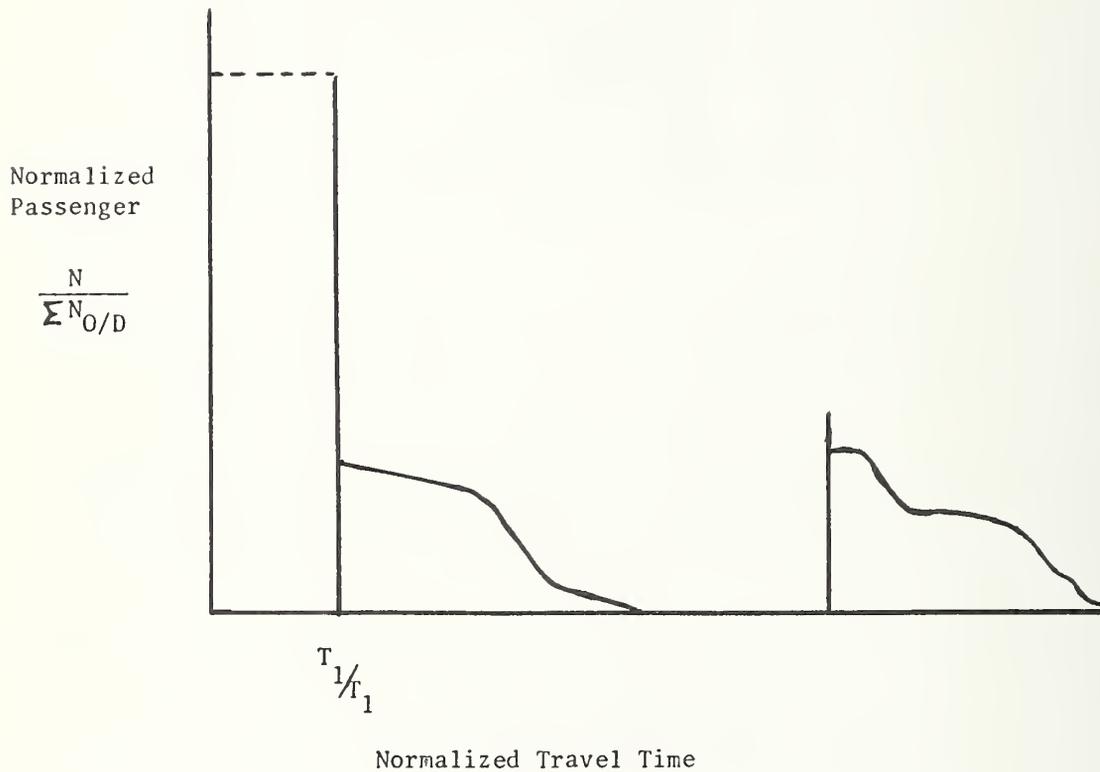


FIGURE 6. AVAILABILITY DISTRIBUTION

1.2 OPERATIONAL PROBABILITIES

The "operational probability" of any element is given by

$$P(t) = P_s(t) + \int_0^t \rho_f(t-\tau) d\tau \int_0^\tau \rho_r(t') P(\tau-t') dt' \quad (15)$$

where (t) is the probability that the element will be operating after time t

$P_S(t)$ is the probability (cumulative) that the element will not fail up to time t ; $P_S(t) = 1 - P_f(t)$, where

$\rho_f(t)$ is the failure density function

$\rho_r(t)$ is the repair density function.

If an exponential failure distribution is assumed for the guideway (Figure 7)

$$\rho_f(t) = \lambda_F e^{-\lambda_F t} \quad (16)$$

and a gamma distribution for the repair (Figure 8)

$$\rho_r(t) = \mu_0^2 t e^{-\mu_0 t} \quad (17)$$

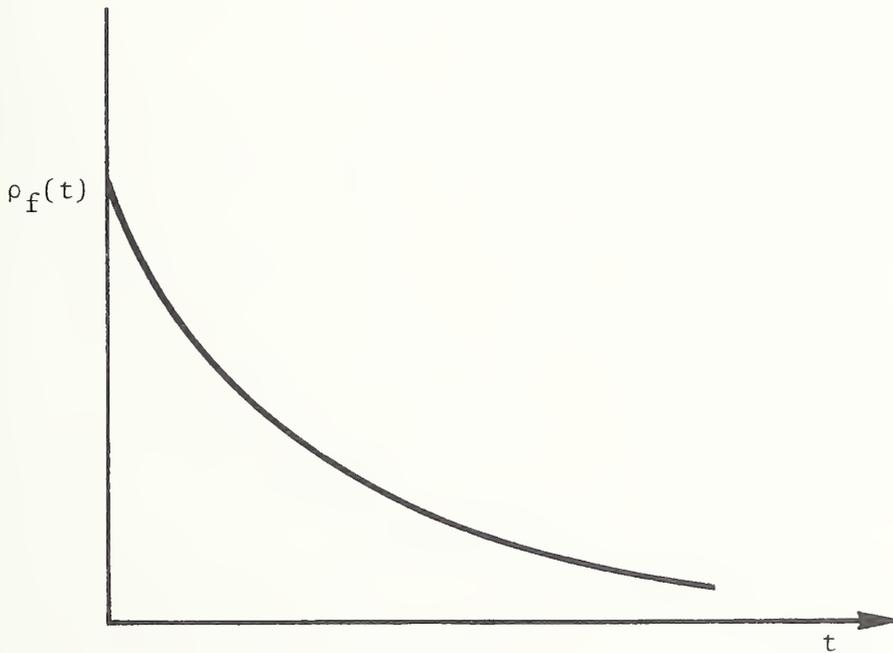


FIGURE 7. FAILURE DISTRIBUTION

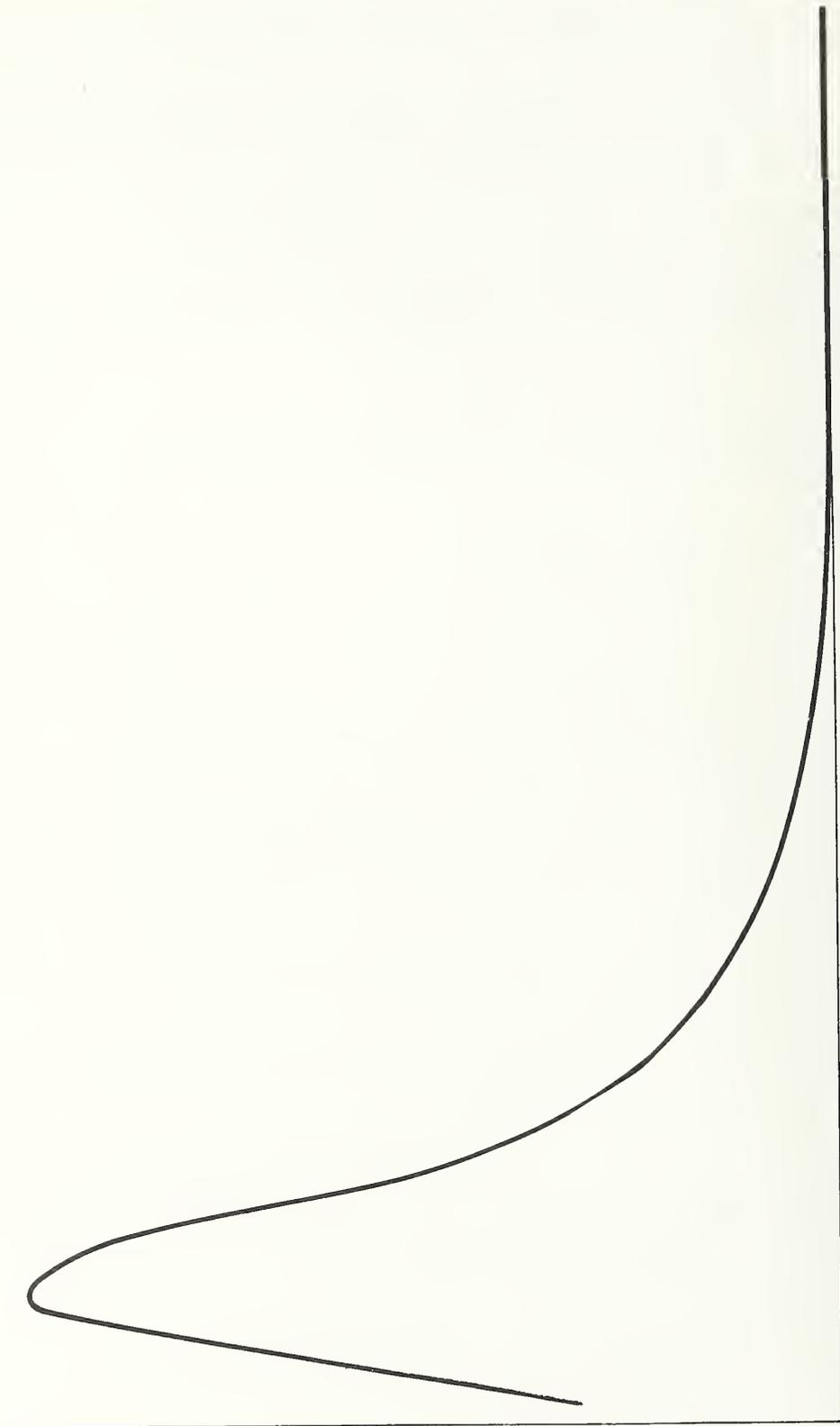


FIGURE 8. GAMMA DISTRIBUTION

Equation (15) can be solved for the guideway (operational probability) by the use of the Laplace transform, yielding

$$P(t) = \frac{\mu_o}{\mu_o + 2\lambda} \left\{ 1 + \left[\sqrt{\frac{\mu_o^2 + 2\mu_o\lambda}{4\mu_o\lambda - \lambda^2}} \left(\frac{4\mu_o^2 + 6\mu_o\lambda + \lambda^2 + 16\mu_o\lambda^3 - 4\lambda^4}{4\mu_o^4} \right) e^{\frac{-2\mu_o + \lambda}{2}t} \right] \cdot \left[\sin \left(\frac{\sqrt{4\mu_o\lambda - \lambda^2}}{2} t + \psi \right) \right] \right\} \quad (18)$$

where λ is the 1/MTBF for the failure distribution and μ_o is the 2/MTTR for the repair distribution.

An example of this is for an element with an MTTR of 30 minutes and an MTBF of 750 hours. Then the operational probability is

$$P(t) = 0.999337775 + 134.307e^{-.0673t} \sin(0.256t + \psi) \quad (19)$$

Evaluation of this expression indicates that the element is in steady state in about three time constants, or about 44.5 minutes. That is for the numbers shown here. If the element is used by a party for more than 44 minutes, the probability of operating is 0.999337775. Also, the value of the steady-state term is extremely close to unity.

The above analysis yields the probability that any single element such as a guideway link or a vehicle is operating. If any of the N vehicles on the link are inoperative, the link will be out of service. The component of the "operational probability" due to a vehicle failure on a link is composed of two parts: (1) the failure probability distribution of any vehicle on the link raised to the power of the number of vehicles on the link; and (2) the repair distribution of a single vehicle. This statement is based on the assumption that failures of more than one vehicle at a time are improbable. The terms needed for deriving the "operational probability" are then

1) the repair probability distribution,

$$P_R(t) = \mu_o^2 t e^{-\mu_o t} \quad (20)$$

2) the probability of any vehicle failing and blocking the link. The probability is given by

$$P(\text{all vehicles not failing}) = P(V_1)P(V_2)P(V_3)\dots P(V_N)$$

where $P(V_\lambda)$ is the probability of the vehicle not failing = $P_S(t)$

If all vehicles are identical, then

$$P_S(t) = [1 - P_F(t)]^N \quad (21)$$

Assuming again an exponential failure probability for any vehicle of the form

$$P_{f_V}(t) = 1 - e^{-\lambda F_V t} \quad (22)$$

$$P_S(t) = e^{-N\lambda F_V t} \quad (23)$$

This is the same form as the success distribution used previously with the exception of an N in the exponent. Therefore, the same "operational probability" distribution can be used with λ replaced by $N\lambda$. This means the individual vehicle MTBF is scaled by the number of vehicles on the link. The link operational probability is given by

$$P(\ell_m) = 1 - \overline{P(\ell_m)} = 1 - [P(G)\overline{P(V_N)} + \overline{P(V_N)}P(G_N) + \overline{P(V_N)}\overline{P(G_N)}]$$

For the steady state case considered in the previous section, this link operational probability is then

$$P(\ell_m) = 1 - \left[\frac{\mu_{oG}}{\mu_{oG} + 2\lambda_G} \left(1 - \frac{\mu_{oV}}{\mu_{oV} + 2N\lambda_V} \right) + \frac{\mu_{oV}}{\mu_{oV} + 2N\lambda_V} \left(1 - \frac{\mu_{oG}}{\mu_{oG} + 2\lambda_G} \right) - \left(1 - \frac{\mu_{oV}}{\mu_{oV} + 2N\lambda_V} \right) \left(1 - \frac{\mu_{oG}}{\mu_{oG} + 2\lambda_G} \right) \right]$$

The station operational probabilities are again the same expression with the station MTBFs and MTRs.

2. EXAMPLE OF AVAILABILITY ANALYSIS

The link operational probabilities for a typical AGT network shown in Figure 9 are given in Table 1. This table includes the average number of vehicles on each link at any instant of time, the link "operational probability", and the guideway and vehicle components of this probability. Also included are the probability of a vehicle failing during the vehicle exposure time and the guideway failing. The numbers in this table were generated for an average load of 14,708 passengers per hour, with a load factor of four passengers per vehicle. The MTBFs and MTTRs used were as follows:

	MTBF (hrs)	MTTR (min)
Vehicle	1000	5
Guideway	5000	30

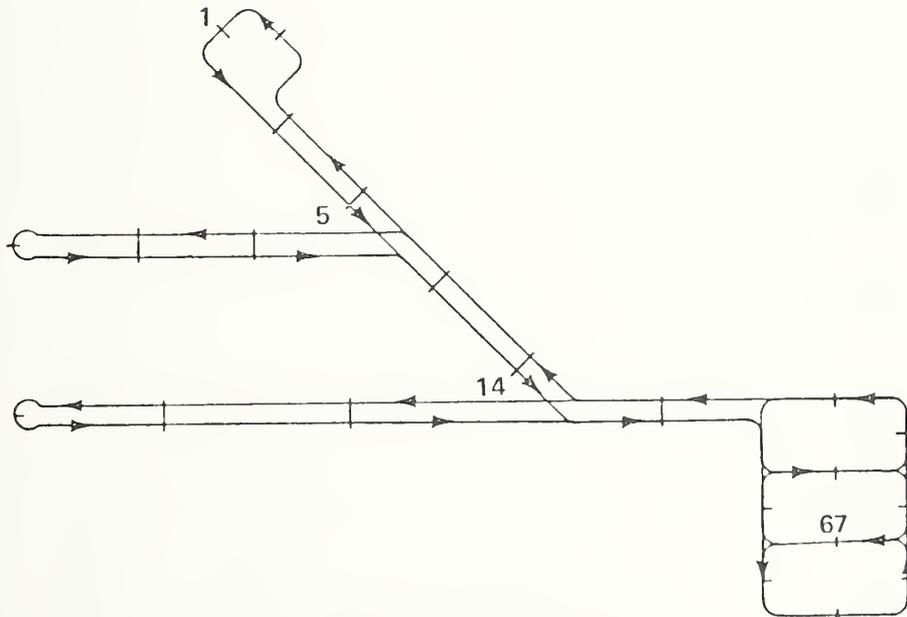


FIGURE 9. HPPRT TEST NETWORK

"Operational Probabilities" for the O/D pairs in this network are given in Table 2.

TABLE 1. LINK "OPERATIONAL" PROBABILITIES*

LINK	LOAD	LK AVAIL.	CB AVAIL.	VA AVAIL.	LINK PF	VEH PF	LINK	LOAD	LK AVAIL.	CB AVAIL.	VA AVAIL.	LINK PF	VEH PF
1	0.61	0.99985	0.99990	0.99995	0.00000	0.00000	2	0.23	0.99988	0.99990	0.99998	0.00001	0.00000
3	0.61	0.99985	0.99990	0.99995	0.00000	0.00000	4	0.83	0.99983	0.99990	0.99993	0.00003	0.00001
5	0.61	0.99985	0.99990	0.99995	0.00000	0.00000	6	0.23	0.99988	0.99990	0.99998	0.00000	0.00000

503

504

* Note: For this example, data similar to those shown for links 1 through 6 are to be provided for 504 links.

TABLE 2. OPERATIONAL PROBABILITIES*

O/D PROBABILITIES ROUTE=1	2	3	4	5	6	7	8	9	10
ORIGIN/DESTINATION									
1	0.0	0.9999	0.0	0.9991	0.0	0.0	0.0	0.0	0.0
2	0.9996	0.0	0.0	0.9987	0.0	0.0	0.0	0.0	0.0
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75									

* Note: Operational probabilities on additional sheets will be given with the same O/D Probabilities under column headings indicated below:

(Sheet 2)	11	12	13	14	15	16	19	20	21	22
(Sheet 3)	23	24	44	48	52	56	57	62	63	67
(Sheet 4)	71	75								

(End of Paper 3 Presentation)

Mr. King (BART)

I have a feeling that one of the things that we always start to do is to define a failure, and whether or not it's practical may depend on your definition of a failure.

Mr. Tucker

We had about twenty failure modes that we included in this particular approach, and that also involved MTTRS. It involved the classes of the system, the different elements of the system like the vehicle, guideway, station merge, demerge, communications, and three or four failure modes with end modes. So, I'm not advocating that for an analytic approach you need to get that level of detail. If you could take those elements and look at a type of failure you know, like a vehicle blocking of the guideway, that, I think, is adequate enough so you can apply the analytic results. Now again, in order to use the analytic approach, it has to be simple, so that you can solve it and have confidence in the answer. After you've had what you think is your baseline system, you can apply the results to a little more detailed simulation like, perhaps, a Smith simulation. But you don't want to do that very often, at least not in complex networks, because computer times are too long.

Mr. Pawlak (TSC)

Maybe I didn't understand how the chart is drawn, but I didn't see any crossovers. Has anybody figured out how often you can reasonably tolerate crossovers with double-tracked guideways in these classes of systems and their inherent reliability, and how much route flexibility you can get with just the crossover before you start doing the kind of thing you're talking about?

Mr. Tucker

I'm not sure I can answer that question. If there were crossovers occasionally over the route, that would show up as one of the alternate routes through the program. In the computation of the probabilities for that alternate route with crossovers, the

reliability of that crossover would also be in that formulation. I think you're asking if you can go through and look at the guideway and make these judgments before you've even started. Is that right?

Mr. Pawlak

Right.

Mr. Tucker

I think you can do that using engineering judgment. A line system has only one way to get to the central business district. With a thousand vehicles per hour, you know that any failure is going to cause problems. So, initially look for at least one alternate route.

Comment from the Audience

When you consider the density of, say, an outbound lane at peak hours, with one vehicle every few seconds, it's sort of hard to use a crossover concept. If there were vehicles shuttling in the inbound lane to pick up passengers every 15 seconds, it's hard to overcome an outbound failure by crossover.

Mr. Pawlak

The kind of failure you're talking about is the vehicle down dead on the guideway.

Dr. Anderson

That doesn't have to be the case. It's possible that the vehicle is capable of being pushed or towed.

Mr. Pawlak

Then you don't use the crossover system.

Dr. Anderson

Well, you might if you want to reroute around it, to see if it's backed up.

Dr. Heimann (TSC)

It was mentioned that there can be several kinds of failure modes. Your equations showed just one kind. Do you, in other analyses, consider various kinds, multiple or different types of failures?

Dr. Anderson

Yes, and the formulation allows you to put it in. But for the case presented here, we just chose one case to simplify. Some of the failure modes are less critical than others, and tend to be almost negligible. But those can be included in the formulation. (End of discussion on Paper 3)

I think we should now move on to the next paper. One of the main things I got out of that, is that if you don't have alternative paths and you don't have a pushing strategy, then the MTBF requirements for line-haul automated systems are just out of this world. The trick is to figure out a rapid pushing strategy, or otherwise, to have frequent alternate paths. I don't know any other choices because MTBFs of twenty, or thirty, or a hundred thousand hours appear impossible.

The next paper is by Bob Oglesby of the GM Transportation Systems Division. Bob has devoted nearly two decades to the product assurance field, and has held a number of staff and supervisor positions in areas ranging from design and development to manufacture and field use. He has also designed computers, and has directed groups for programming computers. Recently, he headed the GM product assurance team for GM's dual-mode contract, which included the assurance of reliability, maintainability, availability, safety, security, and environmental effects. Currently he's responsible for those aspects devoted to availability of GM's System Operations Studies (SOS) contract with DOT/TSC. In addition, he's directing the developing of all the SOS software, and has further responsibility for all SOS subcontract efforts. The title of his paper is, "The Simulation of Availability in AGT Systems."

Mr. Oglesby

Thank you. The important question that I will address is how one should make the translation from an availability goal to hardware, software and operational requirements. I will do that by briefly describing some of GM's dual-mode work.

PANEL 3
PAPER 4

THE SIMULATION OF AVAILABILITY
IN AGT SYSTEMS

R. N. OGLESBY

THE SIMULATION OF AVAILABILITY IN AGT SYSTEMS

R. N. OGLESBY

In the design of a complex, automated ground transportation system such as the dual-mode, it became necessary to establish techniques for evaluating design decisions made during the course of systems development. This included control of failure rates and delay times, which further implied control of redundancies for use in case of a failure. Convenient methods have accomplished this, in terms of establishing the goals for availability rather than what might have been done, namely, just the prediction of availability. Availability for the dual-mode was expressed as the ratio of the time the system would be in operation without failure-caused delays, to the total operation time including delays. For simplicity, it was assumed that an acceptable level of availability based on vehicle service would correspond to an acceptable level of passenger service. By contrast, in the System Operations Studies availability work, we will be developing a definition of availability based on passengers and a definition based on vehicles. In addition, in place of the analytical delay calculations of the dual-mode work, a detailed simulation of the development of those passenger and vehicle delays will be used. Refer to the tabulated topics below for the methods and approach that were adopted.

Methods and Approach

Failure Rate Predictions

Delay Predictions

Monte Carlo Availability Process

Goal Establishment and Allocation

Designs for Achievement.

In order to predict availability-related failure rates, a block diagram of the system concept was constructed showing component relationship, component hardware was defined, and delay-causing failures and failure rates were determined. This sequence is summarized in the listing below.

Failure Rate Prediction

- Block Diagram of System Concept
- Component Hardware Definition
- Delay-Causing Failures
- Failure Rates.

Performance of an extensive failure mode analysis was an integral part of the prediction of failure rates. Failure mode analysis consists of the steps shown in the following listing.

Failure Mode Analysis

- Mechanism Drawing
- Mechanism Functional Block Diagram
- Component Functional Description
- Failure Mode and Effects Work Sheets.

The above items are illustrated respectively in Figures 1 and 2 and Tables 1 and 2.

To ensure completeness, a fault tree analysis was included as a listing and also in the form of a logic diagram (Figure 3) in which the AND and OR gates were used for interfacing of failure modes, hazards, safety parameters, and multiple failures. The fault tree listing included the items noted below.

Fault Tree Analysis

- Logic Symbols
- Faults/Hazards
- Errors
- Multiple Failures

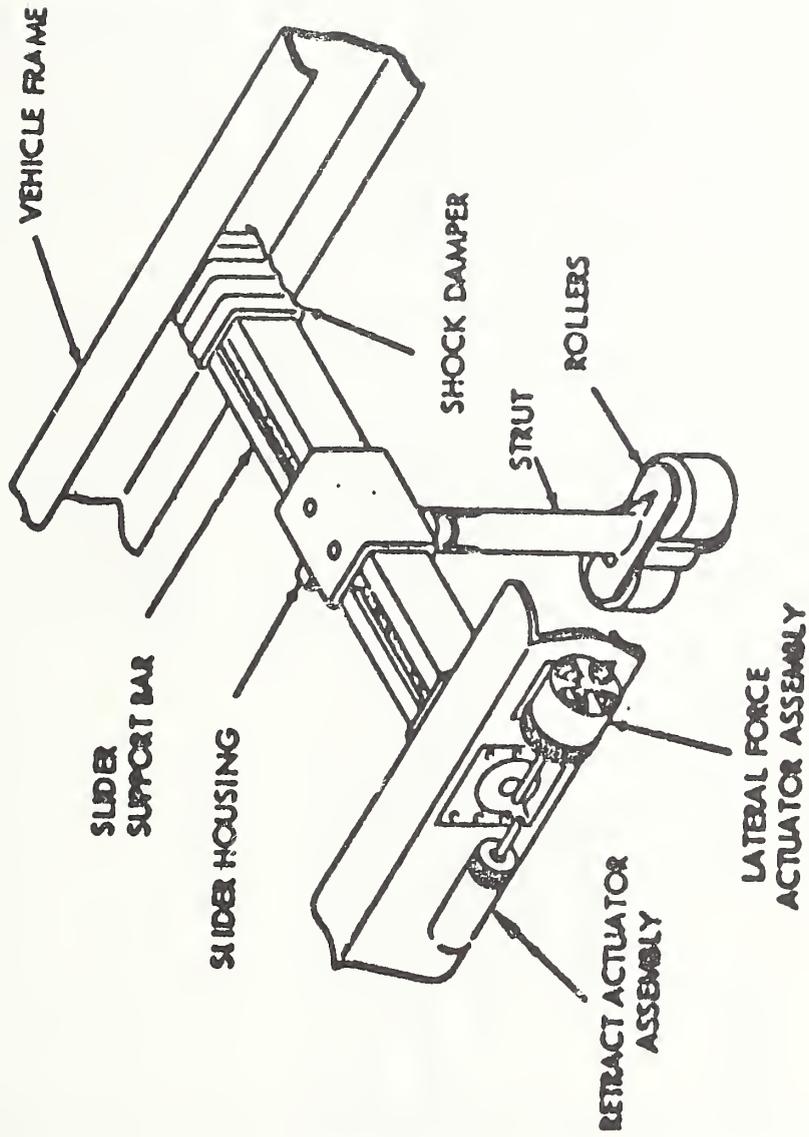


FIGURE 1. POSITIVE SWITCHING MECHANISM

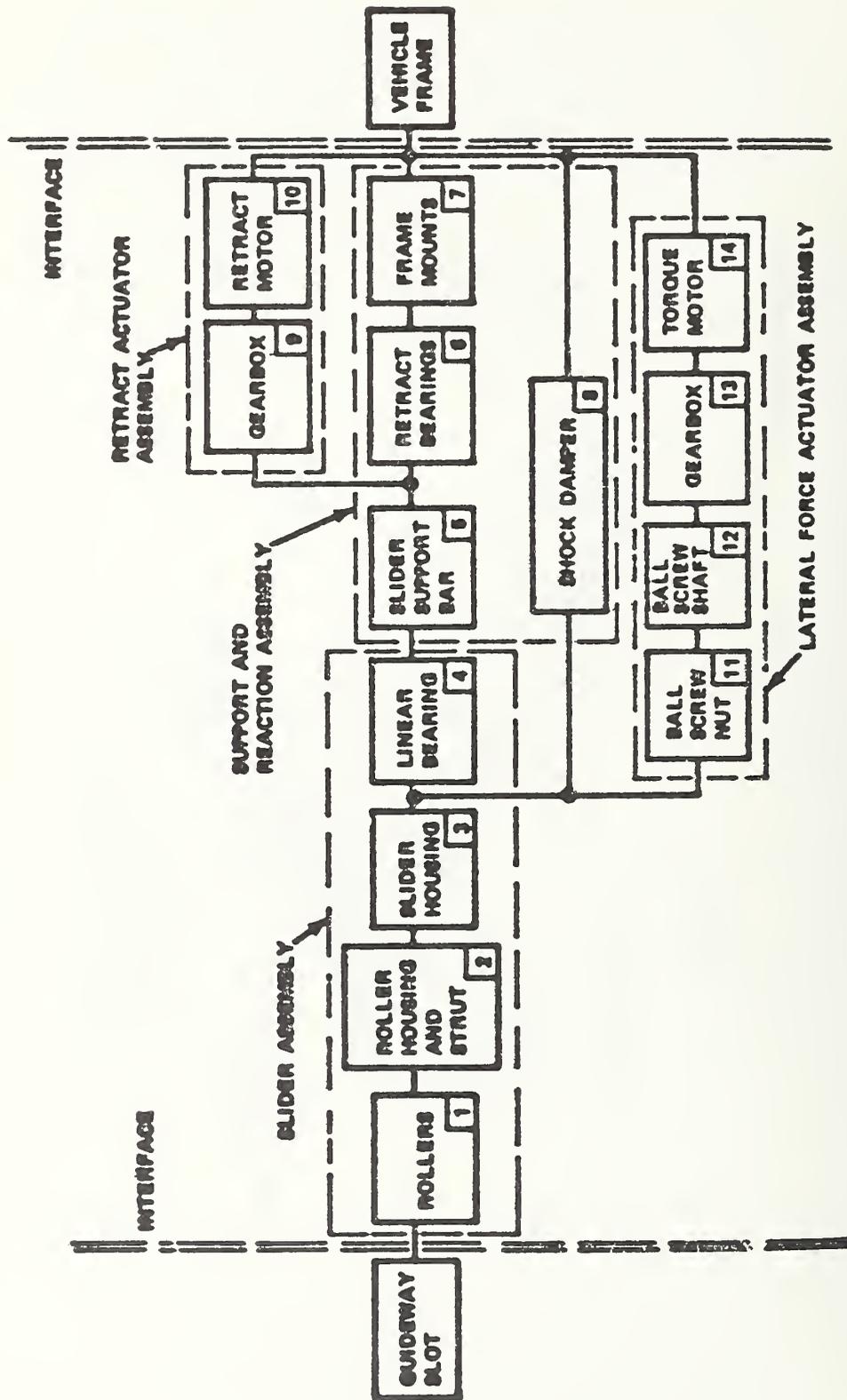


FIGURE 2. POSITIVE SWITCHING MECHANISM BLOCK DIAGRAM

TABLE 1. POSITIVE SWITCHING MECHANISM COMPONENT FUNCTIONS

ASSEMBLY	COMPONENT OR SUBASSEMBLY	COMP. NO.	FUNCTION	
Slider Assembly	Rollers	1.	a. Minimize friction between mechanism and guideway slot	
	Roller housing and strut	2.	a. Transmit lateral guidance forces between slider housing and rollers	
	Slider housing	3.	a. Transmit lateral guidance forces between strut and shock damper b. Rotate strut/roller assembly 90° during mechanism retract/extend cycle	
	Linear bearing	4.	a. Minimize friction between slider housing and slider support bar	
	Slider support bar		5.	a. Transmit lateral guidance forces between linear bearing and frame mounts.
			b. Transmit extend/retract torque between slider assembly and retract actuator assembly	
	Retract bearings	6.	a. Minimize friction between slider support bar and frame mounts during extend/retract motions	
	Frame mounts	7.	a. Transmit lateral guidance forces between slider support bar and vehicle frame	
Shock damper	8.	a. Absorb a portion of the vehicle lateral kinetic energy during operation of the switching mechanism following a primary guidance failure to minimize lateral vehicle acceleration		

TABLE 1. POSITIVE SWITCHING MECHANISM COMPONENT FUNCTIONS (CONTINUED)

ASSEMBLY	COMPONENT OR SUBASSEMBLY	COMP. NO.	FUNCTION
Retract Actuator Assembly	Gearbox	9.	a. Multiply torque of retract motor and transmit it to the slider support bar
	Retract Motor	10.	a. Generate torque to retract mechanism and to assure full extension
Lateral Force Actuator Assembly	Ball screw nut	11.	a. Minimize friction of screw thread b. Transmit lateral bias force between screw shaft and slider housing
	Screw shaft	12.	a. Convert torque into lateral force
	Gearbox	13.	a. Multiply torque of actuator motor and transmit it to the screw shaft
	Torque motor	14.	a. Generate lateral bias torque

TABLE 2. FAILURE MODE AND EFFECTS ANALYSIS

SUBSYSTEM COMPONENT Positive Switching Mechanism Slider Assembly

FUNCTION	FAILURE MODE	FAILURE RATE	FAILURE MECHANISM	EFFECT OF FAILURE ON		FAILURE CLASS		CONTROLS
				SYSTEM	VEHICLE	DELAY	SAFETY PERE.	
(1) Minimize friction	Locked		Bearing seized Shaft bent Roller distorted	Passenger delay during vehicle change	Undesirable noise and rapid wearout of rollers	3	2	1 Driver observation during mode interchange sequence
	Noisy		Bearing deteriorated Roller surface deteriorated	Vehicle out of service for maintenance	Undesirable noise resulting in vehicle out of service when convenient	5	4	3 Routine maintenance or driver observation
(2) Transmit lateral guidance forces	Will not support lateral forces		Housing broken Strut broken	Potential passenger injury, vehicle damage, etc.	Potential of collision with switch "frog" following LACS failure	5	2	1 DBE checks and mechanical overdesign
	Misalignment		Housing distorted Strut bent	Vehicle out of service for maintenance	Potential of noise and excessive wear of rollers	5	4	3 Routine maintenance inspection
(3) Transmit lateral guidance forces	Will not support lateral forces		Housing broken	Potential passenger injury, vehicle damage, etc.	Potential of collision with switch "frog" following LACS failure	5	2	1 DBE checks and mechanical overdesign
	Rotate strut, roller during extend/retract		Rotate mechanism broken Rotate bearing seized	Passenger delay during vehicle change	Unable to complete DBE mode interchange sequence	3	4	1 DBE check of mechanism position
(4) Minimize friction	Seized		Broken bearing, Distorted housing	Potential of vehicle stoppage	Potential of wrong path selection at diverge switch	1-3	2	1 DBE check of lateral cycling time
	Noisy		Deteriorated bearing Deteriorated race (slider bar)	Vehicle out of service for maintenance	Undesirable noise resulting in vehicle out of service for maintenance	5	4	3 Routine maintenance inspection or driver observation

¹ A potential of collision with guideway exists only when the mechanism fails following a primary guidance (LACS) failure. Because a primary guidance failure dictates an emergency shut-down, the additional mechanical failure does not influence the delay already in progress; thus the "5" Delay failure class rating.

² For the same reasons described in ¹ an emergency shut-down is not required for this failure because it is already in progress thus the "1-2" Safety failure class rating.

³ Depending on the random characteristics of the failure the Delay Failure Class may be 1 (vehicle stoppage on guideway) or simply 3 (passenger delay while changing vehicle).

Predictions of vehicle delays began by starting an operational scenario to which the proposed system can be applied. The scenario provided insight and possible strategies to be employed during system operation, defined parameters such as the number of vehicles in the system guideway configuration, passenger flow rates, and headway requirements. This enabled an understanding of possible reaction of the system to subsystem hardware problems or failures, and potential vehicle delays which might be experienced. The determination of the extent of such delays included consideration of vehicles which might be affected by the failed vehicle. The number of vehicles in a queue is a function of flow rates and recovery times. The total delay is determined analytically as the sum of the delays, considering all delayed vehicles.

We performed a computerized system availability program for dual mode, using a Monte Carlo process (Figure 4). The program is designed to utilize inputs from the system's configuration information, component failure rates, operational recovery strategy information, vehicle delay times, and calendar period to be simulated. The program determined random selection of what, where, and when the next failure was to occur. The operational time and delay associated with each failure event is totaled on the system level.

It was a very important feature of the dual mode exercise to establish a goal for availability rather than merely saying, "Well, this is what we've got." The goal was established in the following manner. An initial prediction was made that turned out to be 99.7%. Unfortunately, four vehicle stoppages on guideway per day were associated with that prediction. The number of vehicles involved and the number of stoppages created some concern, from the safety point of view. Although every stoppage was theoretically fail-safe, the more stoppages that occurred per day, the more concern there was, in fact, that a hazard was being created. Therefore, we developed a second criterion, a number independent of the availability number itself. We required that no more than one failure on guideway per day would be tolerated for this particular configuration. A 99.9% figure was then evaluated, but that

MONTE CARLO PROCESS

PROGRAM INPUTS

SYSTEM CONFIGURATION INFORMATION

COMPONENT FAILURE RATES

OPERATIONAL AND RECOVERY STRATEGIES INFORMATION

VEHICLE DELAY TIMES

CALENDAR PERIOD DESIRED TO SIMULATE

PROGRAM DETERMINATIONS

RANDOM SELECTION OF WHICH COMPONENT WOULD FAIL NEXT,
WHEN, AND WHERE

OPERATIONAL TIME AND DELAY AT EACH SIMULATED FAILURE EVENT

SYSTEM TOTAL VEHICLE OPERATING TIME

SYSTEM TOTAL VEHICLE DELAYS

PROGRAM OUTPUT

SYSTEM AVAILABILITY OBSERVED OVER FULL PERIOD OF
SIMULATED OPERATIONAL USE

FIGURE 4. COMPUTERIZED SYSTEM AVAILABILITY PROGRAM FOR
DUAL MODE, USING MONTE CARLO PROCESS

figure turned out to be too costly to implement, and beyond the state of the art. The goal finally arrived at from these configurations was 99.8% vehicle availability, with no more than one on-guideway vehicle stopping per day. The apportionment of the system availability requirement for subsystems was then accomplished based on weighting factors proportional to the particular failure rates, predicted dealy times, and complexity of the subsystems. The apportionment of the subsystem requirements also made use of the Monte Carlo computer program in order to verify that the new configurations did combine to produce the correct overall goal. In addition, vehicle service apportionment involving the questions of useful life of components with selected maintenance practices, procedures for recovery of failed vehicles, and degraded operation studies were all made consistent with the availability number.

Typical failure rates that resulted from the apportionment of availability are shown in Figure 5. The Class A category refers to those failures serious enough to require stoppage on guideway. These, then, are typical of hardware requirements resulting from the overall availability goal.

Performance based on availability apportionment was used as a guide for a number of system configurations decisions; for example, the analysis applied in determining that a backup propulsion system was needed to provide the required level of availability to the system.

In summary, then, the design control that availability provides for such systems can be broken down as follows:

It provides an acceptable maximum frequency of service interruption.

It provides an acceptable level of delay duration.

The appropriate reliabilities for safety related to equipment can be more easily determined.

Redundancies, fail-operational, and fail-graceful designs are established where needed.

AVAILABILITY DEPENDENT FAILURE RATES

SUBSYSTEM	λ	CLASS A λ
VEHICLE	157.2	18.8
GUIDEWAY	142.5	< 0.1
STATION & MODE INTERCHANGE (SMI)	57	< 0.1
MAINTENANCE FACILITY, AUXILIARY EQUIPMENT	57	< 0.1
DIAGNOSTIC BAY EQUIPMENT (DBE)	571	< 0.1
VEHICLE AUTOMATIC CONTROL EQUIPMENT (VAC)	445	80.8
VLF/LF & GUIDEWAY COMMUNICATION EQUIPMENT (GCE)	1010	31.8
SYSTEM MANAGEMENT COMPUTER (SMC)	57	51.8
SECTOR COMPUTER (SC)	57	< 0.1
SYSTEM MANAGEMENT & OPERATIONAL EQUIPMENT (SMO)	114	< 0.1
UHF COMMUNICATIONS EQUIPMENT (UHF)	80	< 0.1

NOTE: λ = FAILURES / 10^6 HR

FIGURE 5. FAILURE RATES RELATED TO APPORTIONMENT OF AVAILABILITY

Optimum recovery procedures of equipment can be better established.

More appropriate determinations of the need for, and specification for studing sidings, bypass links, turn-arounds and crossovers, maintenance facilities (kinds and locations), and standby vehicles (number and location) can all be ascertained. (End of Paper 4 Presentation)

Mr. Siddiquee (SRI)

How were the availability-dependent failure rates incorporated?

Mr. Oglesby

The vehicle delay times were analytically calculated for each failure of a vehicle. That came out of the failure mode and effects analysis. Each one of those failure cases, whether it was a vehicle itself that failed, or perhaps a wayside computer that resulted in stoppage of a vehicle, would have associated with it a particular delay time for that vehicle and trailing vehicles. That event, a particular failure mode input to the availability program, combined with events for the other failure rates to produce the overall effect.

The failure rates in the first column of Figure 5 include failure modes that were less than what would produce a delay as perceived by a passenger. On the other hand, "Class A" failure rates were those serious enough to cause a stoppage on guideway. There were several classifications of failure; for example, slow down and proceed at degraded speed to the next station, and so on.

Question from the Audience

Are those numbers that you predicted based on equipment knowledge?

Mr. Oglesby

These numbers represent, as closely as we can determine, actual capability. At the same time, they reflect the apportionment of the goal.

Dr. Anderson

In other words, you both need it and can do it.

Mr. Sadowski (California PUC)

I have some comments, and I'd like to get some reaction from members of the panel, and maybe from some of the audience. I assume that we're starting with some system requirements, that we're trying to describe availability, dependability, and minimum costs. What we're trying to do is to then apportion down to various levels, and assign, say, MTBF numbers to specific subsystems or specific modules, in order to be able to go out to particular manufacturers and say, "You must design a particular piece of equipment that meets an MTBF for 5,000 hours or 10,000 hours." When you demand this of a manufacturer, who in some cases has had limited experience in dealing with requirements of that nature, he'll look at you and say, "How do I design differently for a 10,000-hour MTBF versus a 5,000-hour MTBF?" In fact, I've seen in my experience some manufacturer who will say, "Well, the green ones are 10,000 hours and the red ones are 5,000 hours." And then you say, "Prove it to me. Prove it by test." His reply is, "Do you want me to test for 10,000 hours or statistically maybe 40,000 hours to meet this requirement? That's going to cost a lot of money." And probably the test could be performed under conditions that really won't simulate the requirement to prove it analytically.

Well, I'm a statistician. Give me any problem and I'll prove it analytically. Now, what I'm suggesting here is that you really need the equipment that has to work, but how do you specify it? This will be covered tomorrow in the User-Manufacturer Relationship discussion. What I'm suggesting here is that rather than specifying reliability by the numbers, the buyer should specify the design requirements and the system characteristics that the equipment must meet. For instance, if it's a mechanical piece of equipment, specify the degree of ruggedness. If it's electrical, say if it's the door, specify the transient protection, the redundancy features, or key functions and the environment under which it

must operate. Specify the ability to isolate and to confirm failures or faults, and the repairability characteristics of the equipment. A particular manufacturer will know how to design to that particular set of requirements. I doubt very much that he'll know how to design to a 10,000-hour MTBF versus a 20,000- or 40,000-hour MTBF. That's my comment, and I'd like to get some reaction.

Dr. Doyon

I happen to be director of a new major project at Northeastern University in Boston. This project is a program in reliability, and the question you asked takes us three terms, two nights a week, and 36 weeks to answer. In the first course I do just what you say--tell people how to design for reliability, what it is. And it certainly can't be said in five minutes or in what we have time for today.

The second course is on demonstration techniques--reliability and maintainability. And the third course deals with analysis of complex systems. My answer to such a manufacturer would be that it would be very wise to institute a training program, or else to go to some competent consulting firm and ask for help. But it's no magic process, and you certainly can't say that this red one is 10,000 hours, and this green one is 5,000 hours. The question you asked is a big one.

Mr. Sadowski

Yes, I'm saying also you have to specify that to the manufacturer. If you leave it to him, it's an open area. You want the control over that.

Dr. Doyon

The way to do that is by putting in incentive clauses. I mentioned yesterday to Mr. Smith that one way out is to put incentive clauses into contracts. In my twenty years of experience in the aerospace industry, primarily in reliability, the way we got these things done was to put penalty and incentive clauses in our contracts, and then we got success.

Mr. Gunter (Westinghouse)

I think you have to give the manufacturer the responsibility for some aspects.

Dr. Doyon

We can seek some help from a consultant, but it does not remove his responsibility.

Mr. Gunter

No. What I'm saying is that you can't hold him responsible for mean time to repair and give the maintenance responsibility to somebody else.

Dr. Doyon

I think you can. Yes, you can.

Mr. Gunter

I don't think we'd be willing to take the contract.

Dr. Dayton

There are many factors in the design that affect the kinds of repair.

Mr. Gunter

We can design to a potential mean time to repair, but don't hold us responsible for an actual one if we aren't doing the maintenance.

Dr. Doyon

You are mixing two things here. As far as the actual design of the system logistics is concerned, what you say is true. Let's define what we mean by mean time to repair. Do we mean mean time to repair or mean time to restoration? Those are separate. They're quite different, distinct.

Mr. Gunter

I said the problem is the same with either one. The manufacturer usually has mean time to restore even less under his control. He does have mean time to repair in terms of the design aspect, and this can be demonstrated.

Mr. Sadowski

I said I'd like it to be covered tomorrow. The fact is that you people here are the ones who are setting the analytical framework to define down to the level in which some people have to react. I'd like to comment also in front of you individuals, because you'll be responsible for putting numbers into the specifications. And I think it should be covered in great detail tomorrow, but I think some consideration should be given also today.

Dr. Anderson

I'd like to comment on that. One of the things that I think is very important in advanced automated systems is that we do study and examine the reliability requirements to find out what's feasible and what isn't. It may be that the reliability requirements tell you that if you have to do with a certain kind of equipment, you can't perform the function with adequate reliability. I think it's important that you at least find out where the "ball park" is. Does a vehicle need 10,000 hours, or are 100 hours good enough? That makes a tremendous difference in the way you go about planning.

Dr. Womack (Otis)

I want to make a remark about that. We see a lot of people with RFPs and things like that. By guaranteeing availability, we get very deeply involved with reliability, the mean time to repair and to restore, and everyone's doing that. That means essentially that you have to do the maintenance. Otis is in the maintenance business, as you probably know. With elevators, they guarantee that you'll have only one unscheduled elevator downtime per year; if you have more than that, they have to absorb the cost. They do a very good analysis.

Mr. Corbin (Vought)

I want to object. I think there's an implication here that maybe manufacturers are not fully cognizant of the implications of reliability and maintainability and availability. But at least the three manufacturers who are here I know to be vastly experienced in those areas--Boeing, Westinghouse and Vought have had years of experience in military weapons.

Dr. Womack

Don't leave Otis out!

Dr. Anderson

Excuse me, what are you objecting to?

Mr. Corbin

I object to the implication that the MTBF and MTTR are not understood by the manufacturers.

Dr. Anderson

I'm sorry. Did somebody say that? It's not a question of whether they understand but what do they do in order to respond differently from one set of requirements to another set of requirements? How do you do things differently for one set of requirements versus another set of requirements?

(End of discussion on Paper 4)

The next speaker is Jerry Roesler, from the staff of the Applied Physics Laboratory at Johns Hopkins University. The title of his talk is "A Trip Dependability Model for Automated Group Rapid Transit Network."

PANEL 3

PAPER 5

A TRIP DEPENDABILITY MODEL FOR
AUTOMATED GROUP RAPID TRANSIT
NETWORKS

W. J. ROESLER

A TRIP DEPENDABILITY MODEL FOR AUTOMATED GROUP RAPID TRANSIT NETWORKS*

W. J. ROESLER

Introduction and Overview

This paper provides a brief description of a model for determining the impact of failure-induced network blockages on the ability of a GRT network to provide travel service to its users. For this paper a GRT system is assumed to be characterized by vehicles of intermediate capacity (10-50 passengers) operating under automatic control over fixed guideways between off-line stations. The dependability model^[1] was developed as part of a flow simulation package which provides the capability to assess the effects of trip level and pattern, network layout, and system design characteristics, on the service quality and operational efficiency attributes of a GRT system. The simulation uses a continuous flow model of the movement of trips and vehicles through the network which itself is modeled as a linear graph, with edges representing links and nodes representing stations.

Figure 1 provides an overview of the simulation structure. The network topological layout and travel demands are two basic inputs. The network is defined in terms of a set of connected, one-way links and stations. The travel demands are provided in terms of a trip origin-destination (O/D) matrix giving the rate of trip making between all stations in the network. The Operations Definition module converts the travel demand inputs into the flows of vehicles on the links and through the stations, taking into

*The effort documented in this paper was supported by the Urban Mass Transportation Administration under contract DOT-UT-30010.

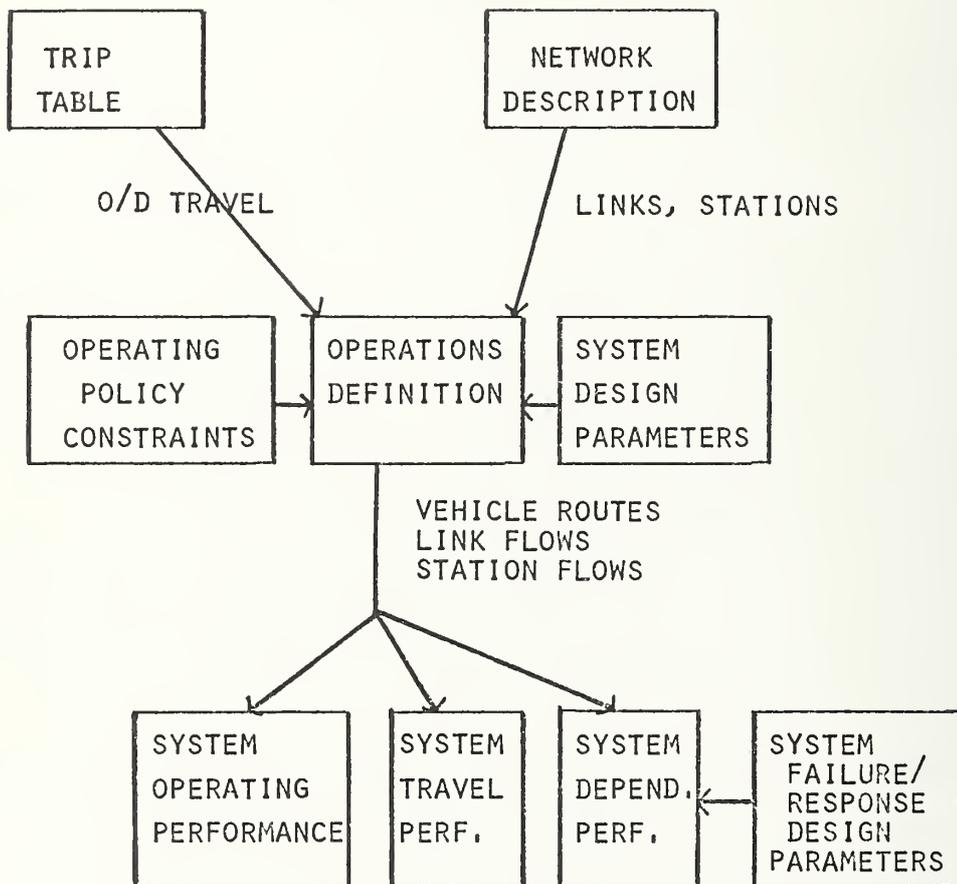


FIGURE 1. FLOW SIMULATION LAYOUT

account particular operating policy constraints and system design parameters such as the allowance of transfers and vehicle size respectively. This module also provides for the conservation of the various vehicle flows by developing flows of empty vehicles to be recycled from locations with imbalances of terminating trips over originating trips to locations where the inverse situation prevails. This module provides the operating policy impact data for the dependability module. The basic outputs are:

- o the routes for travel between all stations in the network in terms of the ordered sequence of links and stations which vehicles travel
- o the times, relative to each origin station, of arriving at each of the links and stations on a route.

The final module computes several operational and service performance measures for the network, including specific summary statistics. The operating statistics computed include:

- o vehicle flow and headway on each link,
- o vehicle flow through each station,
- o active fleet size,
- o total vehicle miles traveled per hour,
- o passenger miles/vehicle mile,
- o vehicle load factor per link, and
- o overall vehicle load factor.

The passenger service measures include trip time, travel speed and wait times for each particular O/D pair as well as aggregated values for the total network. The service performance measures also include those pertaining to trip dependability. The remainder of the paper will concentrate on these performance measures and their method of calculation based on various failure/response system design parameters in the context of the network flow simulation model.

Trip Dependability Definition

The purpose of the network is to provide transportation to the individual traveler in a timely manner. For the traveler, with his particular origin and destination, the trip is successful if the network allows him to complete his trip with a "tolerable" delay. In this model we are only concerned with the impacts of equipment failures on delays. Two aspects of the delays affect the user's judgment of a successful trip:

- o the frequency of a delay
- o the magnitude of the delay when it occurs.

This model develops two related indices to reflect the degree of successfully completing a trip. The first index is the probability of no delay (PND). The second index is the probability of experiencing only a limited delay (PLD). This latter index is considered to reflect the fact that a traveler does not possess a continuous disutility curve for the various delays, but simply regards delays as either within a limit and tolerable, or beyond the limit and excessive. For both indices the probability (or frequency of occurrence) is determined for each O/D pair in the particular network. Various summary statistics are computed to represent overall network performance similar to the manner in which trip speeds between various origins and destinations are combined into a network-oriented travel speed.

For a trip to be successful, the system must be operating when a passenger requests service to a particular destination, and must continue to operate such that he does not experience a delay en-route to his destination. The probabilities which relate these two events to the system design, together with an estimate of the delay, given that a failure occurs, comprise the basic elements of the model.

The approach used in developing these quantities involves:

- o Defining an equipment breakdown structure of the network providing successively more refined design detail

- o Developing the operations-oriented and failure/response-oriented parameters of the structure elements
- o Developing the mathematical relationship for the probability of being operable, the probability of remaining operable while in use, and the delay for each element as functions of the parameters of the elements
- o Computing the trip dependability indices by the algebraic manipulation of the operability state probabilities and delays of the elements.

Network Breakdown Structure

The network breakdown structure (Figure 2) provides the definition of the network in terms of the various levels of system detail. The link and station (element) level is the starting point, since this is the definition level provided in the underlying flow simulation. At the next lower level a link is assumed to consist of the vehicles on the link as well as the main way supporting the vehicles. Similarly, the stations are assumed to be composed of vehicles in the station, the station way, and special passenger-associated equipment. The next level of detail would involve the functional hardware components of the way and vehicles, all of which are assumed identical. For the current uses of the model, vehicles, main way, station way and passenger equipment are considered the lowest level of detail of system equipment. This structure is also useful in considering the definition of a failure at the various levels (Figure 3). To a traveler, a failure occurs if he is delayed. A delay will occur in a continuous flow model if there is a blockage of a link or station. A blockage can result if a vehicle fails on a link, blocking it, or if guideway-associated equipment fails, causing a blockage, and so on. Therefore, for this analysis the failure modes of components are those which result in blockages to the links or stations. A blockage of one link is assumed to be restricted to that link. No secondary blockages are considered. For an analysis of a design by this

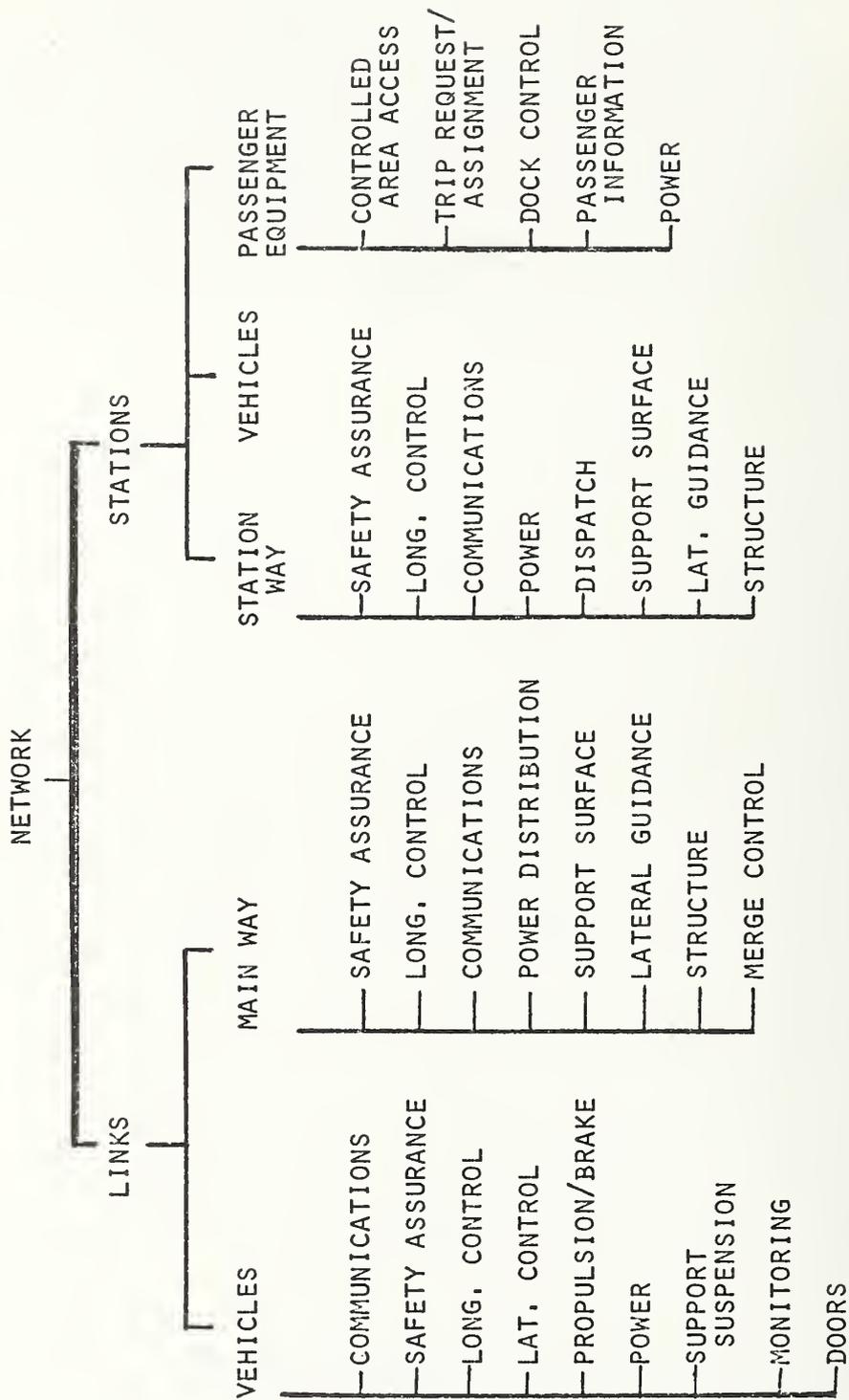


FIGURE 2. NETWORK BREAKDOWN

<u>LEVEL</u>	<u>"FAILED"</u>	<u>"OPERABLE"</u>
I. TRIP	DELAY	NORMAL PROGRESS
II. LINKS STATIONS	BLOCKAGE	DESIGNED FLOW POSSIBLE
III. VEHICLE	DEGRADED LONGI- TUDINAL MOVEMENT	NORMAL MOVEMENT
WAY	DEGRADED FLOW OF VEHICLES	NORMAL VEHICLE PASSAGE
STATION EQUIP.	DEGRADED FLOW OF PASSENGERS	NORMAL PASSENGER PROGRESS

FIGURE 3. SYSTEM FAILED/OPERABLE CONDITIONS

model, a failure mode analysis could be used to derive the component failure rates causing blockages based on specific unit designs. For a dependability parameter allocation study, the component blockage failure rates can be parametrically varied to establish their overall impact on dependability.

Failure/Recovery Parameters

The definition of the failure/recovery system is accomplished through parameters connected with both the elements and components. For automated systems there have been proposals for a number of methods of recovery. These types can be broken into those requiring the on-site efforts of a recovery/repair crew, and those able to be performed by the remote action of an operator. The analysis to date has considered the potential recovery modes shown in Figure 4. The programmed version of the model currently can handle up to four recovery modes for each component.

The recovery time for the restoration of the link or station to an operable status means not only that the cause of the blockage is removed, but that any queue of vehicles which are trapped by the blockage have been redispached. Also, because of the geographic extent of the network, recovery time can be affected by the recovery crew travel time, and, in some cases, by the time to remove a disabled vehicle to a siding. Recovery times in the model have three components. The first, TAR, is the time required for active recovery. This time, which should be determined by designer equipment maintainability studies, is analogous to the active repair time of conventional maintainability analyses. The second component of recovery time is the time associated with network travel, TRT, required in the recovery operation. This time is not only a function of the recovery mode, but also of the location of the individual links and stations with respect to maintenance crew locations and sidings. Each element in the model has associated with it the appropriate value of TRT for the various failure recovery modes, depending upon the locations of the failure recovery system elements.

<u>COMPONENT</u>	<u>RECOVERY MODES</u>
VEHICLE	REMOTE RESTART. REMOTE PUSH BY FOLLOWING VEHICLE. ON SITE ACTION W/O RETRIEVAL VEHICLE. RECOVERY WITH RETRIEVAL VEHICLE.
WAY	REMOTE ACTION. ON SITE ACTION.
PASSENGER EQUIPMENT	REMOTE ACTION. ON SITE ACTION.

FIGURE 4. COMPONENT LEVEL RECOVERY MODES

For stations, recovery occurs as soon as the cause of the blockage is removed. However, for links there is an additional component of recovery time to redispach the vehicles which are queued as a result of the blockage. The model defines a dispatch rate for reinitiating vehicles stopped by a blockage for each link. This quantity is an input defined by the analyst based on the traffic loads. The time required for the recovery of each element is computed within the model for each recovery mode.

The model developed to date has focused on the peak hour operations with relatively saturated links. The network topologies used for GRT indicate that there are relatively few alternative paths between stations. As a result, the use of rerouting is not considered as a failure management option. However, simply to assume that vehicles flow unrestricted into a blockage is unreasonable. Calculation of the link recovery time in the model assumes that no more vehicles are assigned to routes crossing a blocked link after a blockage occurs until the link is again operable. Passengers not yet accepted by the system for those routes are considered to be queued on the station platform, and are provided with service after blockage has been removed. Passengers enroute are assumed to travel until a blockage is reached. The impact of this failure management assumption is that there is a finite limit to the number of vehicles which can be queued on a link by a blockage. A schematic drawing of the link recovery model is shown in Figure 5. The delays to passengers in the model are determined by the time spent queued, and are computed using similar principles.

Element Dependability Factors and Failure Response Parameters

Based on the assumed failure management policy, an element will not cause a delay to a passenger if it is operable when the trip is requested, and if it is operable when required while the trip is enroute. The probabilities associated with these events are basic for development of the trip dependability indices. The probability that an element is operable when the trip is requested, A , is represented by the availability of the element or the

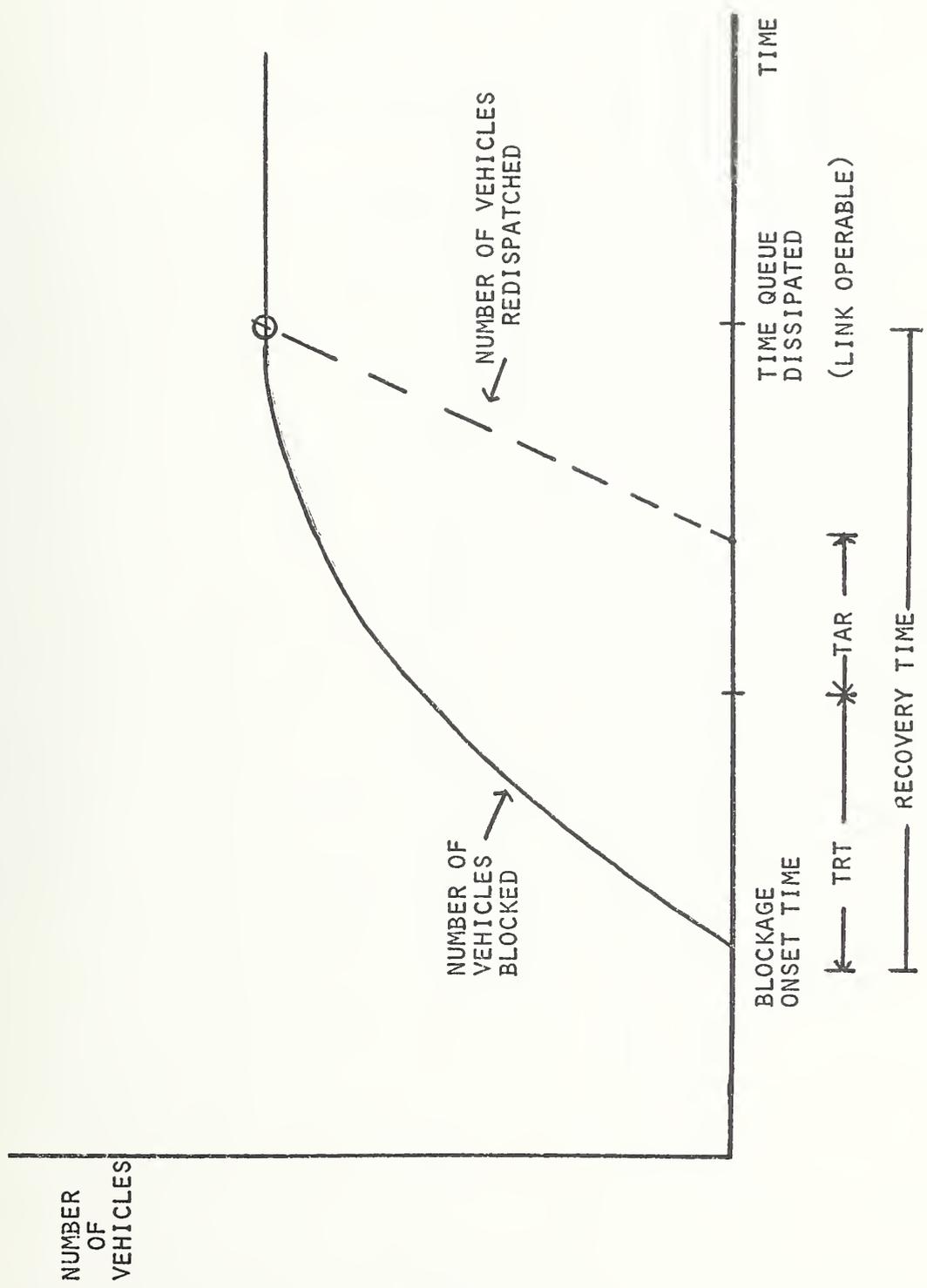


FIGURE 5. LINK RECOVERY TIME FACTORS

fraction of total operating time that the system is up. The general form of the equation used to represent this is shown in Figure 6. The specific values of elements are computed within the model, considering the components which make up the element to be in a reliability series chain arrangement and using the appropriate mathematical expressions given in [1].

The event that an element is operable when required while the trip is enroute is somewhat peculiar to the geographical extent, finite speed of travel, and modular design of transit networks. Once the trip is accepted and the passenger starts his journey, he uses various elements of the network at successive times and for various durations. Once a trip has passed over a link or through an intermediate station, a failure to that element does not directly affect the trip. Therefore, the operability of an element while the passenger is enroute is taken to mean that the element must be operable when the trip is about to use it, i.e., at his time of arrival at the element based on network travel times; in addition, the element must remain operable for the duration of the passengers' use of the element. The probability of element operability when about to be used, P , is given by the expressions for the time-dependent probability of an element being operable, given that it was operable at the start of the trip. The probability expressions are functions of the failure rate, the recovery time, and time at which the element is first needed by the trip. They are computed in the model by considering the element to be a reliability series chain of the components which are part of an alternating failure renewal process.

The probability involving the non-failure while an element is in use is simply the reliability of the element, R . In the model, reliability is assumed to be given by an exponential expression involving the failure rate and the time of exposure of the trip to the element. Again, the reliability of an element is obtained from the components making up the element by assuming a series relationship between the components.

The detailed mathematical functions for these probability expressions as well as for the various delays are provided in [1].

Pr { OPERABLE WHEN TRIP REQUESTED } = A(B,T)

$$A = \frac{1}{1 + BT}$$

Pr { OPERABLE WHEN NEEDED ENROUTE/OPERABLE INITIALLY } = P(B,T,TOA)

$$P = \frac{1}{1 + BT} \left[1 + B \cdot T \cdot \text{EXP} \left\{ - \frac{1 + BT}{T} \cdot \text{TOA} \right\} \right]$$

Pr { OPERABLE WHILE USED } = R(B, TE)

$$R = \text{EXP} \left\{ - B \cdot \text{TE} \right\}$$

FIGURE 6. COMPONENT DEPENDABILITY PROBABILITIES

Combining Elements Into Trip

The final process for developing the trip-related indices consists in combining the element data. The data from the operations definition model delineates the sequence of links and stations, the time of arrival of a trip at these elements, and the time that a trip is exposed to each element, Figure 7. The mathematical expression for the probability of no delay (PND) for a trip between origin and destination is shown in Figure 8. In the computer model the terms are expanded to include the various recovery modes possible. The subscripts indicate which network elements comprise a route. Note that the elements upstream of the station in time equal to the waiting time of the route are included as affecting the dependability of a particular trip. The expression for no delay at intermediate stations relates the fact that a vehicle will bypass a station if the station is not operable on arrival. In order for the passengers' vehicle to be delayed in an intermediate stop station, the station must be operating when the vehicle arrives, and fail when the vehicle is in the station.

The expression used in calculating the probability of a tolerable delay is shown in Figure 9. The expression which in the computer model is expanded to include multiple recovery modes is the summation of those probabilities for which the time delay is greater than the preset threshold.

The matrix of these expressions, as well as the expected delays for each O/D pair in a network, provides the basic data on trip dependability. Network summary measures depicting averages, extremes, and distributions can be generated. While the best overall network measure to be used may be open to debate, it should be noted that any measure averaged over the relative number of trips in the O/D table is desensitized to changes in the system design. The use of the tails of distributions or extreme values seem to be better measures. In addition, an argument can be made that the purpose of the model was not to consider average conditions but to explore the range of conditions prevailing in a transit network. A passenger cares little what happens on the

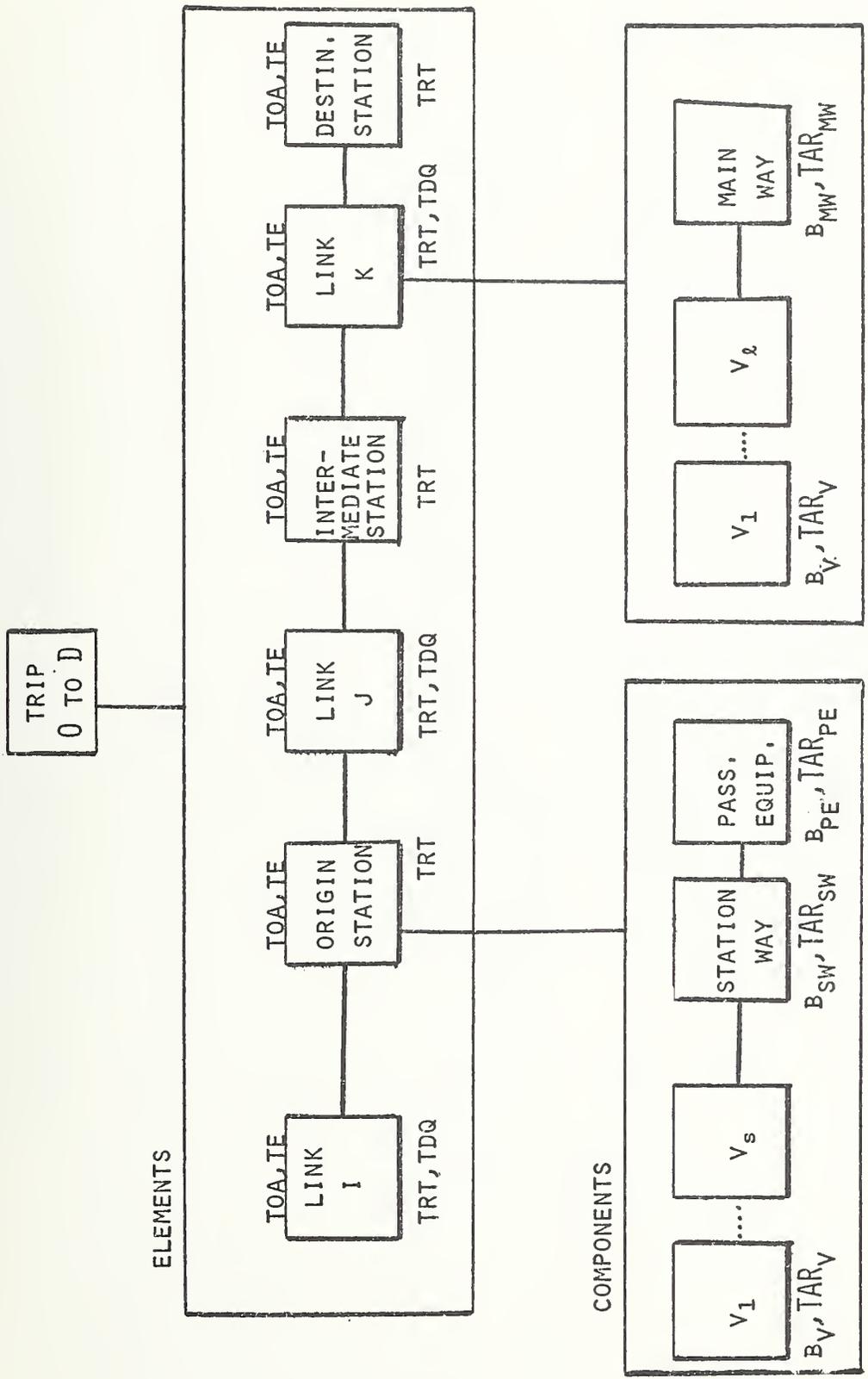


FIGURE 7. TRIP ELEMENT IDENTIFICATION AND BREAKDOWN

$$PND(O,D) = A_{s=0} \cdot A_{\ell} \cdot R_{\ell} \cdot \prod_{\ell \in (L|O,D)} (A_{\ell}) \cdot R_{s=0}$$

$$\cdot \prod_{\ell \in (L|O,D)} (P_{\ell} \cdot R_{\ell}) \cdot \prod_{s \in (S|O,D)} [1 - A_s(1 - R_s)]$$

$$\cdot P_{s=D} \cdot R_{s=D}$$

WHERE

O IS THE ORIGIN STATION,

D IS THE DESTINATION STATION,

ℓ^* IS THE LINK UPSTREAM OF THE ORIGIN ON WHICH THE PASSENGER'S VEHICLE IS TRAVELING WHEN THE WAITING TIME BEGINS,

L IS THE SET OF LINKS EXTENDING FROM ℓ^* THROUGH THE ORIGIN STATION TO THE DESTINATION STATION, WHICH IS THE PATH THE VEHICLE WILL TAKE WHILE SERVING THE TRIP, AND

IS IS THE SET OF STATIONS EXCLUDING THE ORIGIN AND DESTINATION AT WHICH THE VEHICLE IS SCHEDULED TO STOP WHILE SERVING THE TRIP.

FIGURE 8. PROBABILITY OF NO DELAY

$$\begin{aligned}
\text{PDL}(0, D | \theta) &= (1 - A_{s=0})^{\delta_{s=0}} + (1 - A_{s=D})^{\delta_{s=D}} + (1 - A_{\ell^*})^{\delta_{\ell^*}} \\
&+ (1 - R_{\ell^*})^{\delta_{\ell^*}} + \sum_{\ell \in (L|0, D)} (1 - A_{\ell})^{\delta_{\ell}} \\
&+ (1 - R_{s=0})^{\delta_{s=0}} \\
&+ \sum_{\ell \in (L|0, D)} [(1 - P_{\ell}) + (1 - R_{\ell})]^{\delta_{\ell}} \\
&+ \sum_{s \in (S|0, D)} A_s (1 - R_s)^{\delta_s} + (1 - P_{s=D})^{\delta_{\text{REJ}}} \\
&+ P_{s=D} (1 - R_{s=D})^{\delta_{s=D}}
\end{aligned}$$

WHERE

$$\delta_{\epsilon} = \begin{cases} 0 & \text{IF } DL_{\epsilon} < \theta \\ 1 & \text{IF } DL_{\epsilon} \geq \theta \end{cases}$$

DL_{ϵ} IS THE PASSENGER TIME DELAY DUE TO COMPONENT FAILURES ON THE ELEMENT OF THE TRIP,

$$\text{PTD}(0, D | \theta) = 1 - \text{PDL}(0, D | \theta)$$

FIGURE 9. PROBABILITY OF EXCESSIVE/TOLERABLE DELAY

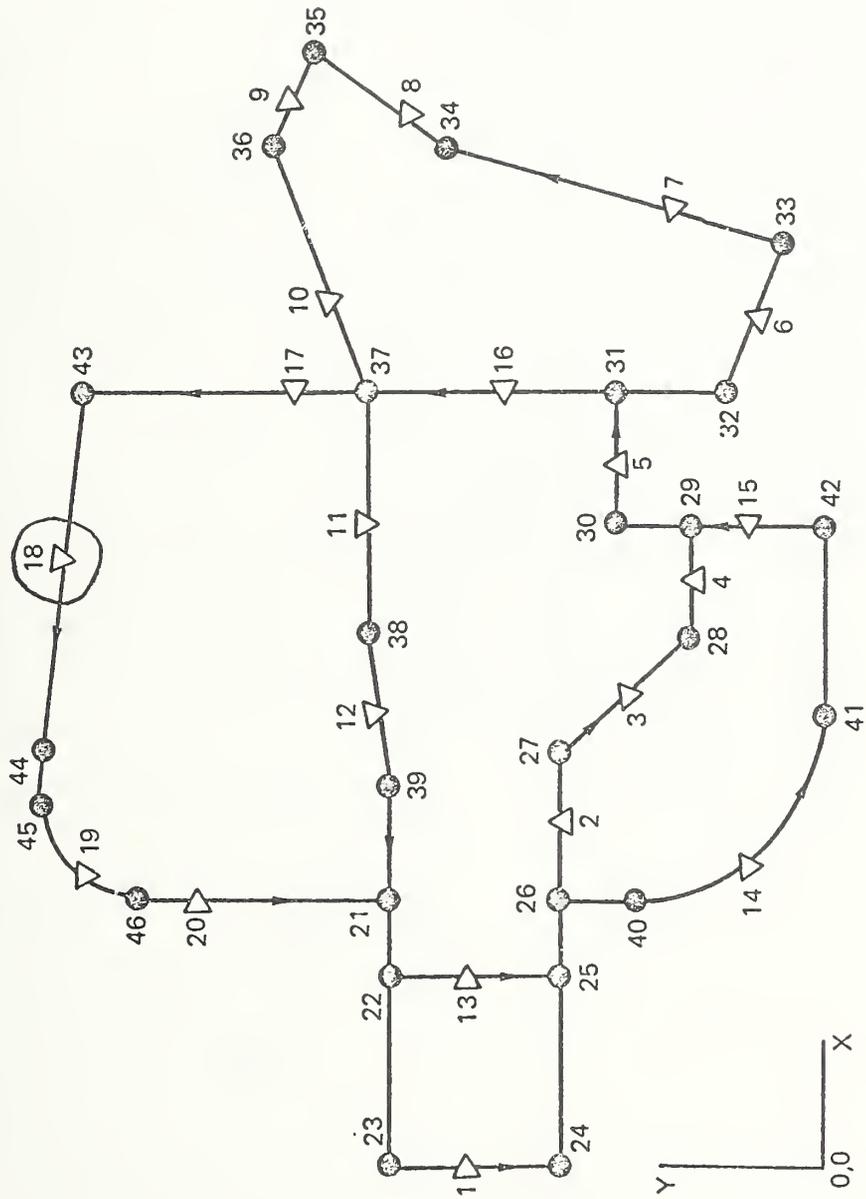
average in the network. He is interested in his trip made when he makes it. Therefore, it is useful to find the degree to which specific trips are provided with dependable service.

Some Examples

The dependability model is programmed as a module of the Flow Simulation Package, and has been used in a preliminary concept design study of the operating characteristics of GRT systems.^[2] The objective of the study was to observe the sensitivity of operating characteristics to system design and operating policy variables. Two network configurations were considered: (1) a 7.5 lane mile, two-loop CBD circulation system with 20 off-line stations, Figure 10; and (2) a 200 lane mile urban regional system with 58 station locations or 104 single direction off-line stations, Figure 11. Peak hour demand levels of 5000 passengers per hour and 60,000 passengers per hour distributed by origin and destination were assumed for the CBD and urban networks respectively. For both networks a fixed route, limited stop service structure was used as the basic peak hour operating policy.

The basic parameters of the dependability model were chosen after review of a number of studies, and generally represent "ball park" figures which are reasonable for GRT systems and which provide a reasonable starting point for sensitivity studies. Figure 12 shows the basic dependability assessment values used. A redispach rate of one vehicle every 10 seconds from a blockage was used uniformly for all links in all stations. In the small CBD network only one location for a retrieval vehicle was considered, while the urban network contained five. Regarding the component blockage and recovery parameters the nominal vehicle MTBF was 1000 hrs/vehicle, although this parameter was varied. The relative proportions of recovery modes represent what is considered a potential for GRT. A more detailed design fault and failure mode analysis would be required to determine if these are

- Nonstation Nodal Elements
- △ Station/Yard Nodal Elements



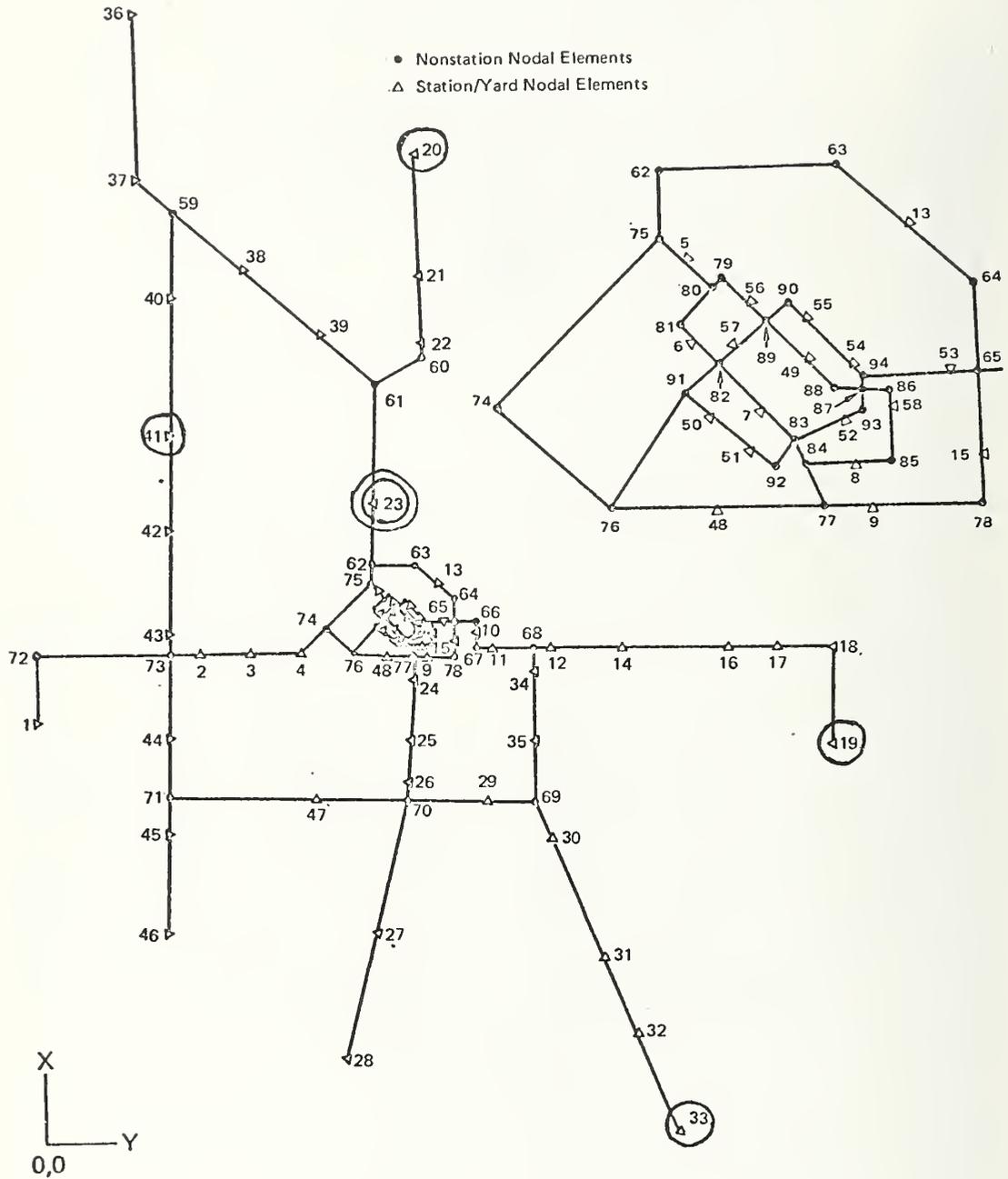


FIGURE 11. NETWORK MODEL E: FULL URBAN REGIONAL NETWORK

	NETWORK	
	CBD	URBAN
VEHICLE REDISPATCH RATE (VEH/HR.)	360	360
RETRIEVAL VEHICLE LOCATIONS	1	5
TOLERABLE DELAY THRESHOLD (MIN.)	3	6

COMPONENT BLOCKAGE/RECOVERY PARAMETERS

COMPONENT	MTBF (HRS)	RECOVERY MODE	PERCENT OF BLOCKAGES	ACTIVE RECOVERY TIME (HR.)
VEHICLE	1000/VEH.	REMOTE RESTART	70	.1
		REMOTE PUSHING	20	.15
		ON SITE ACTION	5	.3
		RETRIEVAL VEHICLE	5	.4
WAY	5000/LANE MI.	REMOTE ACTION	70	.05
		ON SITE ACTION	30	.50
STATION EQUIP.	5000/STA.	REMOTE ACTION	70	.05
		ON SITE ACTION	30	.50

FIGURE 12. DEPENDABILITY ASSESSMENT PARAMETERS

reasonable. For the way equipment on each link we have assumed a constant failure rate per mile of way. Different links have different failure rates due to varying lengths.

Rather than show the detailed matrices of data the synoptic measures are provided. For the probability of no failure induced delay, both the average value based on the relative proportion of trips and the minimum value taken over all possible O/D pairs are provided. These same quantities were also derived for the probability of a tolerable delay, i.e., for a delay less than 3 minutes for the CBD network and less than 6 minutes for the urban network. In addition to these values, the percentage of trips in the network with a 5 percent or greater chance of a delay longer than the tolerable delay was computed. In operational terms, considering the trip to be of a commuter nature, this measure gives the percentage of trips which would suffer an excessive delay one or more times every two weeks.

The data for several runs of the simulation are given in Figure 13. In the first four runs the CBD network was used. These runs illustrate the trade-off between operating policy designs (transfers or no transfers) and improved vehicle reliability. These data indicate that either increasing the vehicle MTBF to 1000 hrs. or allowing transfers provides the same level of service improvement over a system with a 500 hr. vehicle MTBF using a no transfer policy. Improving the vehicle MTBF to 1000 hrs. and using transfers results in even higher quality service. Figure 14 provides a more graphic illustration of these trade-offs.

The next three cases in Figure 13 illustrate the effect of changing a system design parameter, the vehicle capacity, and its impact on dependability for the urban regional network. The data indicate that use of larger vehicles has a relatively dramatic effect on the dependability. Comparison of cases 7 and 8 indicates the value of pushing capability. The impact is not particularly dramatic, partly because the assumed fraction

CASE #	1	2	3	4	5	6	7	8	9	10	11
NETWORK	CBD	CBD	CBD	CBD	URBAN						
TRANSFERS	NO	YES	NO	YES	YES	YES	YES	YES	NO	NO	NO
VEH. CAP.	36	36	36	36	12	.24	36	36	36	36	36
MTBF _v	500	500	1000	1000	1000	1000	1000	1000	500	1000	2000
REMOTE PUSH	YES	YES	YES	YES	YES	YES	YES	NO	YES	YES	YES
PROBABILITY OF NO DELAY:											
AVG.	.955	.978	.978	.990	.887	.942	.960	.953	.878	.943	.970
MIN.	.873	.935	.937	.970	.614	.787	.855	.833	.632	.813	.899
PROBABILITY OF TOLERABLE DELAY:											
AVG.	.958	.980	.979	.99	.90	.950	.966	.959	.894	.95	.974
MIN.	.88	.94	.94	.97	.62	.82	.87	.85	.67	.85	.91
PERCENTAGE OF TRIPS WITH ≥ 5% CHANGE OF EXCESSIVE DELAY:	34	1	1	0	76	41	22	31	81	42	9

FIGURE 13. SAMPLE CASE RESULTS

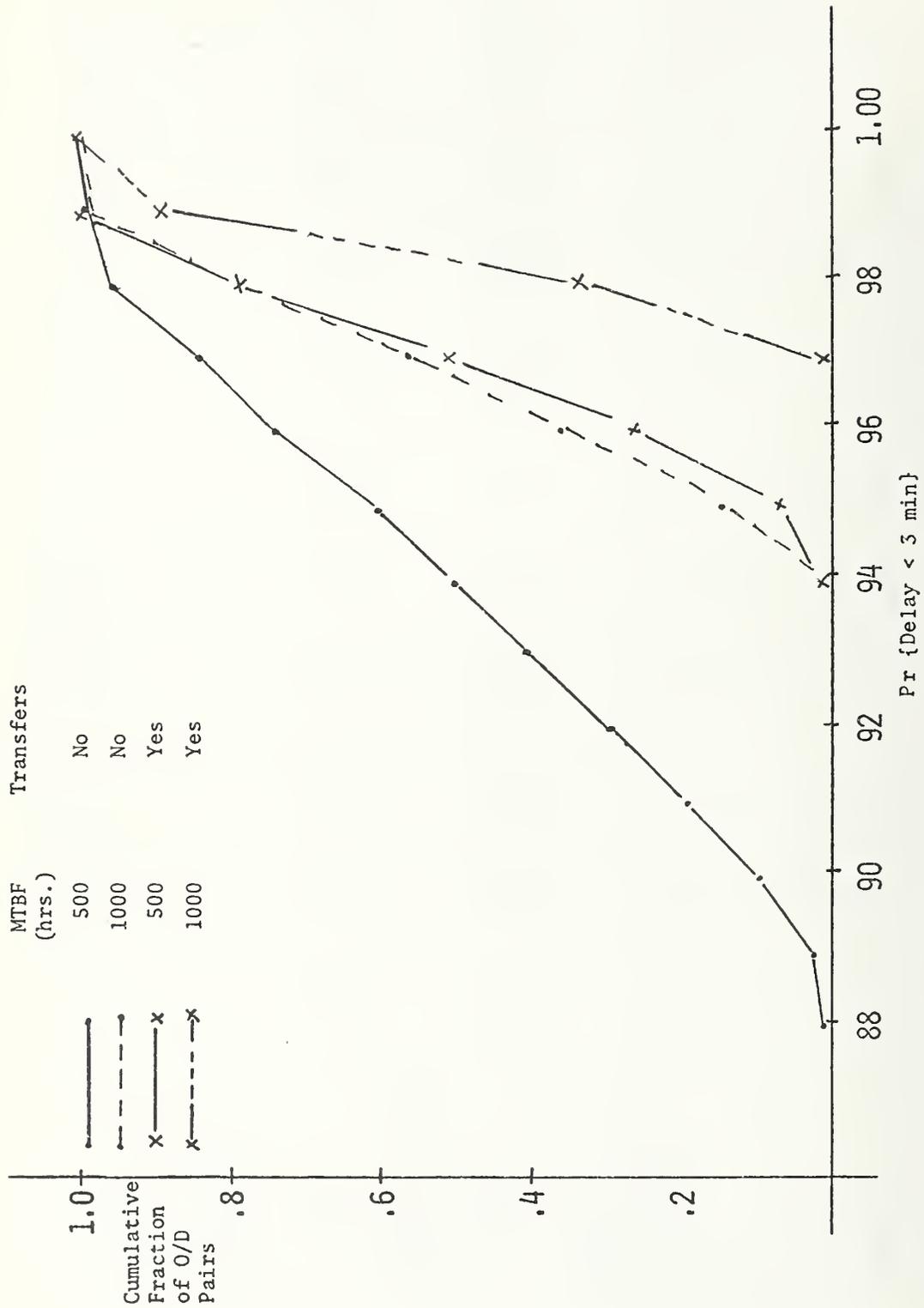


FIGURE 14. IMPACT OF SERVICE POLICY AND VEHICLE FAILURE RATE ON TRIP DEPENDABILITY NETWORK MODEL C-36 PASSENGER VEHICLE

of vehicle-caused blockages is only 20 percent. In some additional cases in which the percentage of pushable failures was increased to 50 percent the value was more pronounced, as would be expected.

Finally, cases 7, 8 and 9 illustrate the effect of varying the vehicle MTBF. The probabilities show a decreasing marginal improvement as the MTBF is increased. However, the percentage of trips likely to incur excessive delay decreases significantly when the higher MTBF is used. This indicates that there is only a relatively small number of trips using the routes which are likely to experience the potentially poorer service conditions. These data are only a sample of what can be obtained from the flow simulation model. Other data reflecting the dependability of the individual links and stations, the expected delays, and the individual trip dependability measures provide valuable information for more penetrating analyses of the impact of design changes. It should be noted that the computer running time for a case in which dependability parameters are varied is only about 20 seconds on an IBM 360/91 for the large urban network. In these runs, the network contains 178 links, 104 stations, and from 1000 to 3000 vehicles with almost 3600 O/D trip pairs to be evaluated. For the smaller network, the running time of the dependability model was much shorter.

Summary

This paper has presented a model for exploring the impact and interaction of network topology, system design characteristics, operating policy design, and system reliability and failure recovery designs on the travel dependability afforded by a GRT system. The model is part of a flow simulation package which provides analytic data useful in the preliminary design of GRT systems in network configurations. Current plans call for the development of a complementary cost model to evaluate both the effectiveness and cost impacts of the various network design options.

REFERENCES

- [1] D. L. Kershner and W. J. Roesler, "Models For Assessing Trip Dependability in Automated Guideway Transit Networks," APL/JHU Report TPR-036, The Applied Physics Laboratory, The Johns Hopkins University, August 1976.
- [2] D. L. Kershner, "An Assessment of Group Rapid Transit System Operating Characteristics," paper presented at the Intersociety Transportation Conference, Los Angeles, California, July 1976.

(End of Paper 5 Presentation)

Dr. Anderson

Thank you very much, Jerry. To allow the next speakers adequate time we'll provide time at the end for general questions. The next speaker is going to take a slightly different tack. He's Dr. Leonard Doyon, Associate Professor of Operations Research at Northeastern University and a Senior Associate of Assurance Technology Corporation. From 1958 to 1975 he was with the Raytheon Company, where he held the positions of Manager of the Reliability and Maintainability Section, Manager of the Product Assurance Department, and Principal Engineer in the Advanced Development Laboratory. During six months in 1975 he was Consultant on Reliability to the French Atomic Energy Commission. He has a PhD Degree in Operations Research. The title of his talk is "AGT Service Availability Modeling." In his talk he will discuss, and also, I believe, enhance, our understanding of Markov chains.

PANEL 3
PAPER 6

AGT SERVICE AVAILABILITY MODELING

LEONARD R. DOYON

AGT SERVICE AVAILABILITY MODELING

L.R. DOYON

INTRODUCTION

The three principal groups of people involved in a transit system, the users, operators and designers, each must have their own needs satisfied in order for the system to be successful. The users need to experience no delay, and/or to arrive at their destinations when planned, and safely; the operators need a low life-cycle cost and a favorable public image; and the designers need to have these translated quantitatively into specification requirements that they can comprehend clearly and verify by reasonable means. To translate these needs quantitatively, measures of performance fulfilling these needs have to be defined and established. Three sets of performance measures are recommended to satisfy the needs of the users, operators, and designers. These three sets of performance measures must also be employed to constrain the hardware parameters, i.e., MTBF and repair times, and the operational parameters, e.g., operational test, failure management approach, and maintenance concept.

PERFORMANCE MEASURES

User Performance Measures

There exists a difference of opinion as to what measure is most important for passenger satisfaction: "experiencing no delay" or "arriving when planned" [Reference 1]. Both are valid needs which are not mutually exclusive. The dynamic dependability equations for the user is developed as follows:

(a) For experiencing no delay:

$$A = \frac{\mu}{\lambda + \mu} \quad (1)$$

= steady-state or equilibrium availability of a PRT vehicle and/or equipment of interest

= probability that a customer arriving at a random point in time at a given station will find the vehicle and/or equipment operational and ready for use

= mean failure rate (λ)* of the vehicles and equipment for failure classes which will result in delay (see Table 1)

= mean repair rate (μ)* of the vehicles and equipment by a given repair crew.

Of course, the word "ready" does not mean instantaneous. A waiting time of two minutes maximum is deemed acceptable [Reference 2, p. 44]. Consequently, we have a dynamic and not a static situation as the above implies. Whether a vehicle and/or equipment will be ready in two minutes depends on whether it is in an operational state or a fail state at the time of arrival of the customer. A more accurate measure is:

$$A_1(t_1) = \frac{\mu}{\lambda + \mu} + \frac{\lambda}{\lambda + \mu} e^{-(\lambda + \mu)t} \quad (2)$$

= the probability the vehicle and/or equipment is operational at time t_1 , two minutes hence, given it was operational initially at time t_0 , the customer arrival time.

*For illustrative purposes, the times-between-failure and times-to-repair are assumed to both obey the exponential probability laws. In actual situations, this simplistic assumption is seldom true. Times-between-failures often obey a mixed exponential-normal probability law; times-to-repair almost always obey a log-normal probability law.

$$A_2(t_1) = \frac{\mu}{\lambda + \mu} - \frac{\mu}{\lambda + \mu} e^{-(\lambda + \mu)t} \quad (3)$$

= the probability the vehicle and/or equipment is operational at time t_1 , two minutes hence, given it was in fail state initially, at time t_0 , the customer arrival time.

Having not experienced a waiting time in excess of two minutes at the station, once he boards a vehicle the passenger also demands no delay in transit, namely:

$$R(\bar{t}) = e^{-\lambda \bar{t}} \quad (4)$$

= probability of no delay in transit for a trip duration of mean time \bar{t} under the assumption that any failure other than in Class Designation 1 (see Table 1) will cause a delay regardless of how short the time to restore the vehicle or equipment to the full operational state.

It is clear, then, that the dependability D as a measure of not experiencing a waiting time in the station in excess of two minutes and no delay in transit time is:

$$D = \left[A_1(t_1) + A_2(t_1) - A_1(t_1)A_2(t_1) \right] R(\bar{t}) \quad (5)$$

A very important feature of the measure "dependability" in this format, as for all equations presented in this paper is that this measure is easily translated into the simple parameters λ_i and μ_i , the allocated failure rate and allocated repair rate down to the lowest hardware level. In this format, the designer need not concern himself with mathematical probability theory and equations. He concerns himself with the specified (allocated) failure rates and repair rates of his particular part of the system as they relate to the failure effects that can occur to his hardware and at

his interfaces with the rest of the system. There will also be some additional qualitative constraints on the design resulting from the maintenance concepts and failure management approaches developed in conjunction with these quantitative parameters.

b) For arriving when planned:

We have more flexibility with this measure than for "experiencing no delay" because, if there is no waiting time at the station, the surplus time extends the time until arrival. Or vice-versa, if the transit time is less than anticipated, the waiting time at the station can be longer. Under this situation waiting time t_1 and transit time t_2 (now a variable instead of a fixed time \bar{t}) are convoluted as follows:

$$D(t_3) = \int_0^{t_3} \int_0^{t_2-t_1} \left[A_1(t_2-t_1) + A_2(t_2-t_1) - A_2(t_2-t_1) \cdot A_2(t_2-t_1) \right] dR(t_2) dt_2 \quad (6)$$

which is more easily calculated in the complex domain of Laplace transforms:

$$D(s) = \left[A_1(s) + A_2(s) - A_1(s) A_2(s) \right] R(s) \quad (7)$$

Close form solutions of these equations are not needed. Iterative solutions are easily obtained with the computer program AFARS as explained in a subsequent paragraph.

Operator Performance Measures

In addition to those measures that keep his customers satisfied, the operator is interested in measures which will minimize his life-cycle cost. The measures of interest to him are:

$$A_0 = \frac{MTBF}{MTBF + MDT} \quad (8)$$

where

MTBF = mean-time between-failure

MDT = mean-downtime, i.e., MTTR plus logistic time

MTTR = mean-time-to-repair

Another cost factor of interest is the system's ability to meet the peaks or rush hour demands:

$$\underline{A}(0,T) = \int_0^T \left[A_1(t_1) + A_2(t_1) - A_1(t_1)A_2(t_1) \right] R(\bar{t}) dt \quad (9)$$

where

$\underline{A}(0,t)$ = Interval or mean availability of a system under transient conditions during a peak or rush hour period of T hours.

This measure will aid the operator in this decision on the size and number of emergency repair crews. For this decision he also needs:

$$\begin{aligned} E[N(T)] &= \sum_{n=1}^N nP_n(T) \\ &= P_1(T) + 2P_2(T) + \dots + NP_N(T) \end{aligned} \quad (10)$$

where

$P_n(T)$ = Probability of n emergency repair crews needed during a rush hour period T

N = The number of repair crews calculated to be necessary to meet an emergency of a given severity level which is calculated to have a probability of occurrence $P_n(T)$ during time T.

The values $P_n(T)$ for $n = 0$ and $n = N$ are obtained with the Markovian state-transition approach using the AFARS computer program described in the next paragraph.

\tilde{M} = median time to repair, or 50% percentile for repair actions

M_{\max} = the maximum value of repair-time that can be tolerated no more than α fraction of the time before the system experiences a serious queuing problem of vehicles. The value for α may be determined or set by policy, say at $\alpha = 0.05$, requiring that the value M_{\max} be exceeded for no more than 5% of the repair actions.

m = mean wear-out-life or longevity of the system. This m is unrelated to the MTBF of the system.

Designer Performance Measures

For a designer, two measures directly under his control are the MTBF (or failure rate λ), and the MTTR (or repair μ) of his equipment. Indirectly, the availability is also under his control, inasmuch as this measure is a function of the other two. The availability equation(s) may be considerably complex and will have to be provided to him by the operator. The designer also needs to know the failure classifications (see Table 1). Other measures directly under his control are m , the mean-wear-out life, and M_{\max} , the tolerable maximum value of the times-to-repair.

To a large degree, he has control over the failure-modes of this equipment, but an assessment of the overall effect of the failures on the total system can be beyond his sole responsibility. A meaningful FMECA (Failure Mode, Effect and Criticality Analysis) for the system is a responsibility he has to share with the operator.

FAILURE MODES AND EFFECTS

The Relationship of Failure Effects to Specifying the Requirements

A basic assumption of the preliminary models of the previous paragraphs is that the system failure modes and effects are fully understood and reflected in the models and their associated requirements. For instance, some failures will cause the vehicle to stop such that it can be pushed/pulled, while others will cause vehicle slowdown (reference the failure effect classifications of Table 1). The preliminary models of the preceding

TABLE 1. VEHICLE FAILURE CLASSES RECOMMENDED

CLASS DESIGNATION	CATEGORY	STATUS OF VEHICLE	EFFECTS OF FAILURE	TYPICAL FAILURES
1	No delay	Normal operation.	Inconsequential. Vehicle continues in service; repair is scheduled at a time which causes no inconvenience or delay to passengers.	Door rattle
2	Minor delay, no collision.	Complete control at full speed.	Loss of time by passengers transferring to another vehicle at nearest station.	Door must be manually closed.
3	Moderate delay, no collision.	Complete control at reduced speed.	Lost time by passengers in a string of vehicles and by passengers in affected vehicle transferring to another vehicle at the nearest station.	Get box cover stuck in station.
4	Minor delay, no collision.	Stopped or required to stop; able to be pushed to next station by next vehicle.	Lost time by passengers in a string of vehicles; and additionally, by passengers in both the affected and adjacent vehicles transferring to other vehicles at the nearest station.	Loss of d-r/w power.
5	Serious delay, no collision.	Immobile; cannot be pushed or pulled; must await rescue vehicle.	Other vehicles must depend on alternate routes; considerable loss of time by many passengers; serious traffic jams may result.	Leaked brake shoe.
6a	Collision of two vehicles.	As for Class 2	Affects on vehicle and lost time same as for Class 2. No hazard, no injury to passengers.	Broken head light.
6b	Collision of two vehicles.	As for Class 3	Effect on vehicle and lost time same as for Class 3. No hazard, no injury to passengers.	Heavy damage to frame.
7	Critical situation.	Immobile; serious collision, or potential or actual hazard to safety of passengers and/or superficial injury to one or more passengers has occurred.	Passive vehicle dispatched; safety precautionary measures imposed but no first aid is necessary; other vehicles must depend on alternate routes; considerable lost time by many passengers; serious traffic jams.	Evidence of impact; door jammed, floor plate pulled out.
8	Catastrophic situation.	Immobile; very serious collision and/or accident or breakdown of equipment has occurred where one or more passengers have been killed and/or have been injured seriously enough to be administered first aid.	Emergency alarm has been sounded; one or more ambulances have been dispatched; other vehicles diverted to alternate routes; serious traffic jams may result.	Flying glass injuring passengers.

paragraphs must be refined to reflect these failure effects. Qualitative constraints concerning the more severe failure effects, i.e., creating a safety hazard or blocking the guideway, must also be established.

Specifying the Service Availability Requirements

Because of the different interests and responsibilities of the user, operator, and designer, three sets of quantitative performance measures have to be derived for an AGT system. Obvious by then, one can expect that there may exist more than one "service availability" model for the system. At least one model must address the needs of the operator. Yet, if more than one model, all models must have one common objective: they have to lead to a specific set of specific numbers and constraints that form the hardware reliability and maintainability requirements; numbers that are calculable and measurable for the designer, and constraints that are understandable and applicable. Furthermore, the service availability models will have to be dynamic, as suggested by equations (5) and (6) for the "dependability".

MODELING THE SERVICE AVAILABILITY

A Proposed Availability Modeling Approach

To be dynamic and accurate, the service availability model for an AGT system will have to consider measures from many engineering disciplines: system analysis, feedback and control, queueing theory, reliability, maintainability, logistic planning and others. The key to bringing together the myriads of parameters from all these disciplines into a single set of manageable parameters is the system-state concept or "state-equations" which form the base of system analysis. The "Rosetta Stone" which makes possible the transformation of parameters into state-equations, is the Markovian state-transition diagram [Reference 3]. The use of the Markovian state-transition diagram to formulate the service-availability models leading to a set of specific numbers for hardware reliability and maintainability requirements is described in the following paragraphs.

Use of Markovian State-Transition Diagrams

Markov-chain theory has been in existence for decades but, largely because the theory has traditionally been presented in mathematical jargon, it has not found broad application in engineering work. The author, in his dissertation published last year [Reference 3], has succeeded in reducing the jargon into engineering language, and in so doing has developed simple Markovian state-transition diagram techniques which find broad application in many engineering disciplines. To date, the technique has been applied with remarkable success by the author to dynamic queueing models,* network planning for management, and availability/reliability/maintainability models of radar systems [Reference 4], nuclear power plants [Reference 5], and aircraft microwave landing systems. AGT systems are extremely adaptable to application of this technique.

*The only known author to date who has used "flow diagrams" to any extent in queueing theory is Klwinrock in Queueing Systems, Vol. I, John Wiley & Sons, 1975, for equilibrium models.

The method has since been improved [Reference 6] to include models having times-between-failures and times-to-repair obeying mixed probability laws. The original computer program (AFARS) has been revised to double-precision [Reference 7]. The revised program also has self error-correction features against numerical-oscillations and rounding-off. errors. The programming logic has also been improved to minimize core storage and execution time. Another important feature of the program revision is the fact that one need not know FORTRAN language to utilize the program AFARS.

Applying the State-Transition Diagram to an AGT System

Inasmuch as the Markovian state-transition diagram method is well documented [References 5 and 8], only one illustrative example is presented herein.

For a more comprehensive application example, one for which the objectives are compatible with those of an AGT system, the reader is urged to read Reference 4. This early application was for arriving at a minimum life-cycle cost for a specific minimum system availability and specified mission success as constraints. The trade-off variables in this study were redundancy of equipment, size of repair crews, and work schedule for the repair crews. The operational scenario, as depicted in Tables 1 and 2 of the reference, vividly illustrate how the scenario could easily be one for an AGT system if the words "Dual Mode Transit System (DMT)", "Shuttle-Loop Transit (SLT)", "Group Rapid Transit (GRT)", and "Personal Rapid Transit (PRT)" were used instead of the word "radar"; "failure-management" instead of "prelaunch alert"; "transit-time" instead of "mission time"; and "passenger delay" instead of "launch delay". Table 3 of the reference provides the same type of statistics that would be used to arrive at life-cycle cost decisions for determining the optimal redundancy needed for safety optimal repair crew sizes, and work schedule for an urban mass transportation system.

The Service Availability, Reliability, and Maintainability Model - An Example

a) The System States

Suppose, for an urban grid network of PRT, that there is a fully automatic switching control monitored by a computer. Also, suppose that for safety reasons, if not for availability or reliability, it is decided to add an active secondary redundant semi-automatic switching control. It is semi-automatic in that only the critical functions are monitored by the computer; the others are monitored by an attendant, obviously only during a time when the primary fully automatic unit is undergoing repair.

For these two controls, there could be two possible distinct sequences of failure events, i.e., there is a "dual" Markov chain. One would be the principal control failing first, followed by failure of the secondary control before the first is restored to service. The second possibility is the converse, namely, the secondary control failing first, followed by the primary control.

It stands to reason, for the first sequence, that failure of the secondary unit would not be cause for the repairman to interrupt his repair work on the primary unit. On the other hand, for the second sequence, the repairman would stop working on the secondary unit and give priority to the primary unit as soon as it fails.

Recognizing these sequences of events and priority of repair given to the primary unit, we define the system states as follows:

State 1: Both control units operational.

State 2: The primary unit is in a fail state; the secondary unit is still operative.

State 3: The primary unit having failed first, the secondary unit is now in a fail state also.

State 4: The secondary unit is in a fail state; the primary unit is still operative.

State 5: The secondary unit having failed first, the primary unit is now in a fail state also.

Let: A = primary unit with failure rate λ_A and repair rate μ_A .

B = Secondary unit with failure rate λ_B and repair rate μ_B .

b) The Reliability Block Diagram

The reliability block diagram for this pair of switching controls and corresponding Markovian state-transition diagram, giving the primary control, Unit A, priority of repair, are shown in Figure 1. No explanation is necessary for the reliability block diagram.

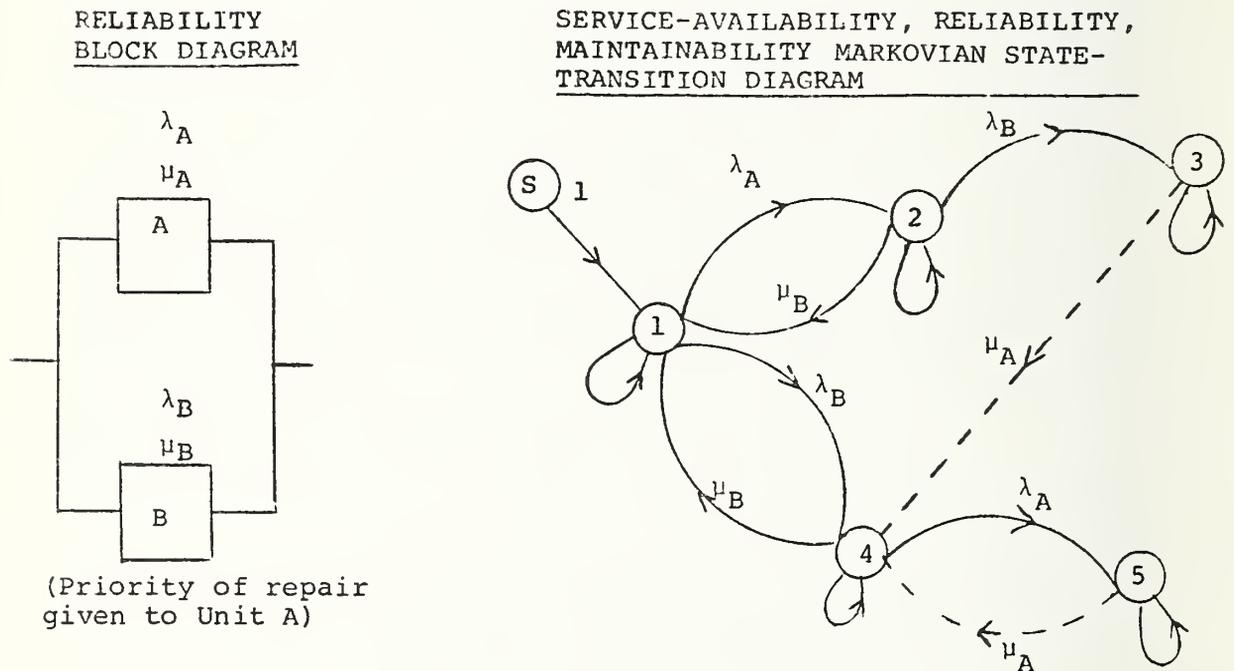


FIGURE 1. THE RELIABILITY BLOCK DIAGRAM AND ITS ASSOCIATED SERVICE AVAILABILITY STATE-TRANSITION DIAGRAM — AN EXAMPLE

c) The Service Availability State-Transition Diagram and Solution

The Markovian diagram, complete with the two broken-line arcs from nodes 4 to 3 and 5 to 3, is for the service availability dynamic model. The elements of the diagram are as follows:

- (1) The nodes represent the states of the system at time $t = nT$, where n is the number of iteration and T is the iteration step-size in the AFARS program explained in a subsequent paragraph.
- (2) The arcs from mode-to-mode represent the state-to-state transition probabilities of the system during an iteration time unit T using the AFARS computer program.
- (3) The self-loops at the nodes represent the probabilities of no change in state in the system during an iteration T .
- (4) The node S , or "trigger", with arc 1 indicates the system is initially in state 1 at time $t = 0$ with probability 1.0.
- (5) The arcs in the "forward" direction (left-to-right) represent the probabilities of failure for times-between-failure obeying a given probability law (exponential or Weibull) with mean failure rates λ_A or λ_B as appropriate. They are the "forward" probabilities of state-to-state transitions for the system.
- (6) The arcs in the "reverse" direction (right-to-left) represent the probabilities of restoration or repair completed during an iteration time-unit T .

The performance measures solved are the probabilities of the system states. For this simple example, they are the probabilities of each of the five states, 1 through 5 defined

above, at time t , the time of interest. With these values ($P_i(t)$), we obtain the solutions:

A(t): The dynamic service availability $A(t)$ of the system initially fully operational (state 1) at $t = 0$ in the complete Markovian diagram as shown, where for $t = nT$:

$$A(nT) = P_1(nT) + P_2(nT) + P_4(nT)$$

The solution, as all solutions, is printed out automatically in the AFARS Program.

A: The equilibrium or steady-state service availability is the $A(t)$ model for n very large in the AFARS program, where for $t \approx \infty$:

$$A = P_1 + P_2 + P_4$$

d) The Reliability State-Transition Diagram and Solution

The reliability state-transition diagram is identical to that shown in Figure 1, except that the two broken-line arcs are deleted. Nothing else changes. Solving the $P_i(t)$ values, the solution is then:

$$R(nt) = P_1(nT) + P_2(nT) + P_4(n)T$$

e) The Maintainability State-Transition Diagram and Solution

The maintainability state-transition diagram consists of the two broken-line arcs only, and the nodes shown in Figure 1. As before, solving the $P_i(t)$ values yields:

M(t): The maintainability $M(t)$ of the system in the above Markovian diagram with all solid line node-to-node arcs removed and with "normalized triggers" added to the nodes 3 and 5 (see Exhibit #2 enclosed), where for $t = nT$:

$$M(nT) = P_2(nT) + P_4(nT)$$

All there remains to do now is to write the necessary state equations by inspection directly from the diagram for solution with the AFARS program as illustrated in the following paragraphs.

Writing The State Equations for AFARS

a) The Data Cards

A computer cannot accept alphabetical subscripts. Therefore, for the above illustrative example, let

λ_1 and $\mu_1 = \lambda_A$ and μ_A respectively

λ_2 and $\mu_2 = \lambda_B$ and μ_B respectively

The numerical values for λ_1 , λ_2 , μ_1 , μ_2 are punched in predesignated fields of specified data cards. In the fields next to each λ and μ the user punches the digit 1 if the times-between-failure or times-to-repair obeys the exponential probability law, or the digit 2 if the times-between-failure is Weibull or if the times-to-repair is lognormal. If Weibull, we punch the value for β ; if lognormal, the value for σ . With the data cards punched, we need only to write the state equations and punch one card for each equation.

b) The State-Equation Cards for the Service Availability Model

The AFARS is already programmed to understand that:

F(1) = the probability of failure during an iteration T for the λ_1 , and probability law punched on the data card.

F(2) = same as F(1) for λ_2 .

G(1) = the probability of repair during an iteration T for the μ_1 and probability law punched on the data card.

G(2) = same as G(1) for μ_2 .

1 - F(1) = probability of no failure for λ_1 during an iteration T.

$1 - F(2) = \text{same as } 1 - F(1) \text{ for } \lambda_2.$

$1 - G(1) = \text{probability of no repair for } \mu_1 \text{ during iteration } T.$

$1 - G(2) = \text{same as } 1 - G(1) \text{ for } \mu_2$

$P(1,2) = \text{probability of a forward transition (a failure event) from state 1 to state 2 during an iteration } T. \text{ Similarly for } P(2,3), P(1,4), \text{ and } P(4,5).$

$P(2,1) = \text{probability of a backward transition (a repair event) from state 2 to state 1 during an iteration } T. \text{ Similarly for } P(4,1), P(3,4), \text{ and } P(5,4).$

$P(1,1) = \text{probability of no change - system remains in state 1 during an iteration of } T. \text{ Similarly for } P(2,2), P(3,3), P(4,4), P(5,5).$

Therefore:

$$P(1,1) = 1.D0 - P(1,2) - P(1,4)$$

meaning that $P(1,1)$ is one minus the probability of transition from state 1 to state 2 or state 1 to state 4. The "D" after the decimal in 1.D0 is written for double precision.

The above is strictly for explanatory purposes; it is not work that has to be done by the user. The user simply writes the state-equations by inspection directly from the diagram as follows:

For node 1: (this and other explanation lines below are not punched)

$$P(1,2) = F(1)$$

$$P(1,4) = F(2)$$

$$P(1,1) = 1.D0 - P(1,2) - P(1,4)$$

For node 2:

$$P(2,3) = F(2) * (1.D0 - G(1))$$

$$P(2,1) = G(1) * (1.D0 - F(2))$$

$$P(2,2) = 1.D0 - P(2,3) - P(2,1)$$

For node 3:

$$P(3,4) = G(1)$$

$$P(3,3) = 1.D0 - P(3,4)$$

For node 4:

$$P(4,5) = F(1)*(1.D0 - G(2))$$

$$P(4,1) = G(2)*(1.D0 - F(1))$$

$$P(4,4) = 1.D0 - P(4,5) - P(4,1)$$

For node 5:

$$P(5,4) = G(1)$$

$$P(5,5) = 1.D0 - P(5,4)$$

The set is now complete. One card is punched for each line above. All that needs to be done to run the program now is to punch in predesignated columns of the data cards:

- (a) the title
- (b) the quantity n , the number of iterations
- (c) the value of T , the iteration step size
NOTE: The product nT must always equal t , the real-time duration of interest.
- (d) which P_i (nT) you want printed (choice of three) and how often printed (every iteration or less often)
- (e) whether the solution desired is $A(t)$, A , \underline{A} ($0,T$), $R(t)$, $M(t)$, MTBF, or MTTR
NOTE: A subroutine integrates $A(t)$ automatically to obtain $A(0,T)$.
- (f) whether curves for three selected P_i (nT) values $A(t)$, $\underline{A}(0,T)$, $R(t)$ or $M(t)$ drawn automatically by the computer are desired.

AFARS is programmed to prevent obtaining invalid results. For example, selection of the size for T is arbitrary. However, if the user selects the value too large, it would cause numerical oscillation. To prevent this, a subroutine checks for numerical oscillations down to the sixteenth significant figure. If such an error is noted, the step-size will automatically be halved (and n doubled) and checked again, and reduced again if necessary. Then the execution is performed, but in the printout the user will be told that the step-size was decreased and what the value is. Conversely, if T is selected too small, causing a rounding-off error in the sixteenth significant figure, a subroutine will automatically double the T (and halve n). If the MTBF is asked for, but the process is non-stationary (namely, the times-between-failure and times-to-repair are not both distributed exponentially), a subroutine will block the execution of the run and print "Process not stationary -- MTBF does not exist!"

c) The State-Equation Cards for the Reliability Model

No cards need to be added or deleted in the above "service availability" card deck for solving the $R(t)$ with the program AFARS. It is only necessary to punch a "2" in a predesignated card to instruct the computer that the solution desired is $R(t)$.

d) The State-Equation Cards for the Maintainability Model

As for solving for $R(t)$, no cards need to be added or deleted in the above "service availability" card deck for solving for $M(t)$ with the program AFARS. It is only necessary to punch a "3" in a predesignated field of one card to instruct the computer that the solution desired is the $M(t)$.

CONCLUSIONS

The Markovian state-transition diagram approach to modeling complex systems is a new, powerful engineering tool. It is a pictorial, rather than a mathematical, description of the physical behavior of a system. It also makes possible the transformation

of the many variables encountered in many disciplines of engineering analysis into a single homogeneous set of probability values, from which solutions for the original variables may then be obtained.

The AFARS computer program offers the engineer a tool for solving the state-equations described by the Markovian state-transition diagram even if the engineer is not versed in computer programming and has little or no knowledge of FORTRAN language.

The combination of the Markovian state-transition diagram technique and the AFARS program, without doubt, will provide the technological breakthrough for arriving at a "real-world" service availability model for AGT and for D.O.T. The model will:

- a) be passenger-related,
- b) lead to a set of specific numbers for hardware reliability and maintainability requirements,
- c) be calculable and measurable, inasmuch as the model will be translatable into quantitative MTBF and MTTR values, for which standard reliability and maintainability demonstration test methods exist (MIL-STD-781 and MIL-STD-471A). These tests assess whether these specified parameters have been achieved by the contractor, and indirectly whether the specified "service availability" has also been achieved.

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(End of Paper 6 Presentation)

Dr. Anderson

Thank you very much, Len. Bob Oglesby wanted to make a comment. We'll allow time for that and then move on to the next paper.

Mr. Oglesby

Thank you very much, Ed. Very briefly I'd like to bring your attention to some work I've done. It bears on the earlier discussion as well as on the Markov discussion that we've just heard. I tried to use the Lagrange multiplier technique for optimization of reliability constraints. I tried it also with the dynamic program technique. The dynamic programming technique has the advantage of finding all optimums, while the Lagrange finds most of the interesting ones. I found this limitation to be more than compensated for by the faster computer speeds involved, going directly to the optimums. In the same exercise I was struck by the familiar problem of redundancy. The model says that the more redundancy you add, the better your reliability gets. Well, that just isn't so. The case of inadvertence very quickly compensates, and one arrives at the limitation for redundancy with only a single element added, two at most. In other cases I find that a single failure mode would affect both redundant elements as well. So, I want to caution you on the application of this technique.

Dr. Anderson

Thank you very much, Bob. The next speaker is Dr. Emanuel Diamant of Deleuw-Cather, of which he is a staff Vice President. He will discuss system aspects of availability.

Dr. Diamant

Thank you, Ed. I first wish to comment that I thoroughly approve of what Jerry Roesler has done. Now I would like to continue with some individual thoughts on the system aspects of service availability.

PANEL 3
PAPER 7

SYSTEM ASPECTS OF SERVICE
AVAILABILITY

E. DIAMANT

SYSTEM ASPECTS OF SERVICE AVAILABILITY

E. DIAMANT

My point of emphasis lies in the methodology of determining availability. I submit that we must try to apply the definition of availability as well as the techniques for its calculation to every transit system and level of service we're talking about. But I'm also aware of the fact that very often, in trying to deal with availability or to simplify the analytical development, we carry out certain simplifications which don't always work to our favor. In the past, analytical simplifications have resulted in reliability requirements which are either impossible to meet in a practical sense, or which have trivialized the problem. If, however, we apply the concept of the level of service in our definition of availability, we can accomplish some things that are important in system design. For one thing, we can look at a system in an evolutionary sense. Systems do not spring up full-blown to their full geographic extent or level of service or level of technology. There are concepts of availability that deal with these various states. We can discriminate among choices that we have in hardware design, in system design, or in operating policies. Finally, I think we can isolate certain components, certain systems, or certain policies to which the system is more critically sensitive in its performance.

My point of departure is to talk about the system's state. I believe that we have to look at each system at a certain baseline level of design. For instance, if we take a system like

WMATA and evaluate the performance of the system today in terms of its state some years in the future, it is going to look pretty poor. The availability definitions and methods of tabulations for that system in its current state are totally different from what they will be. If you apply to it the same measures that you would apply to a system operating at its maximum capacity, then I think you're coming out with a quite incorrect conclusion. This is true with BART, and I think it's going to be true of many of the AGT systems that may be coming in the future.

So, I believe that there are a number of base lines, or design base lines, against which we must measure availability. There isn't a single one. There isn't a finished one. There are a number of these which depend on where we want to deal with the system.

My second observation is that availability is not a simple number or a simple parameter, but a multivariable function. I don't know how one discriminates between the first order and second order parameters, but I believe that availability in the context of a transit system is multivariable. Let me expand on that for a while.

In approaching a suitable definition for availability, I will refer to two commonly accepted aspects of the system - a hard system and a soft system. In the hard system I include the usual items such as physical stations, equipment, and the like. In the soft system I include some other kinds of parameters. In particular, I'm interested in the service parameters and in operational management. Service parameters would include such things as station stop policies (where I stop and where I go); link capacities; and specified travel times. In the design stage I would possibly have to come up with a different definition of these parameters.

In the second group, operational management, I include such things as train makeup and dispatch, fare and management policies, and maintainability.

At a design level, one tries to set the operational management policies to satisfy the service requirements. In reality, there's always a tradeoff and compromise between what you'd like to do and what you think you can accomplish.

(Note: Dr. Diamant proceeds to discuss the system availability of a complex network in terms of link capacities, travel times, equipment reliability, and degree of system maturity. A series of matrices for the various system states is discussed.)

Now what is the utility of all this? It's a good way for a mathematically inclined individual to represent, in a matrix format, the very complex process of a system. It is also a means for distinguishing between certain operational and hardware factors, and for recognizing their interrelationship. There is still another important utility to be aware of, i.e., the ability that one obtains to discriminate between various elements of systems, so that one will not place upon them impossibly difficult requirements.

Let us look at the impact of availability on patronage and costs as they affect the user. One would have to turn his attention toward system capacity in terms of routes as distinct from links and systems. This was done in the Roesler paper. Thus, one could define the availability due to the capacity on a route of a system as the sum of the links involved on that route. The availability of the entire route with all the factors that are included would become another measure. By analogy, the entire system can be described by determining the availability on all the routes.

The question then becomes one of identifying certain links and certain routes which are more critical for the entire operation of a system than others. Now we can focus the requirement for availability on the routes and operational policies which impact

those routes only. It becomes a different story if you define requirements for reliability and restorability for the critical links in the system. I think you would find that in almost every case there are some critical links which carry far more people, and are far more critical to the overall success of the system than the rest of the links. It appears to me quite logical to concentrate on the reliability requirements of the components which impact the operation of that particular link. This approach leads to the ability to visualize effects and to make the kind of decisions that need to be made.

There is one exception that I would like to take with what was said this morning. One of the speakers argued that because computer costs are very high we have to simplify our models. I disagree with that, for the simple reason that if you apply a method in the design phase, no matter how much it costs, I don't think it begins to approach the costs that you will encounter later on when the system is built and loss of revenue and litigations and other irritations plague you. I think it is well worth almost any cost during the design phase to define availability requirements and translate them into hardware requirements, identifying your options both in hardware design and service design. I think the money will be well spent.

(End of Paper 7 Presentation)

Dr. Anderson

Thank you very much, Manny.

Mr. Roesler

I just want to comment on worrying about computer costs. There is a cost effectiveness in modeling too. You want to get as much for your money as you can.

Dr. Anderson

I want to comment on that too, having some involvement in the Denver study. The patronage model was very elaborate, and it was very costly to make a lot of parametric runs; as a result, I think, not enough runs were made.

Comment 1

I'd like to distinguish between a study phase and a design phase. The early portion of the design phase is the time to look at a very detailed analysis and come up with livable specifications for the hardware. Specifications should be dictated by the kind of service and the kinds of network that you are going to get, and by certain policy decisions which the agency must make.

Comment 2

I agree that you need to make those types of runs and details in the design phase, so that you can have a very good estimate of what you're buying. However, I think there are two benefits you get out of an analytic approach by trying to simplify them. First, you get a very good overview of what's happening, and you don't have to make a lot of simulation runs and then look at trends. Secondly, I think that in any program it's desirable to be as close to reality as possible. But on some of these large simulations, detailed or coarse, the runs on the computers do get very expensive, and you do want to reduce the costs. Of course, you don't want to jeopardize the effectiveness of the analysis. I don't think anyone would suggest that.

Mr. Marino

I would just like to second what Manny Diamant said about worrying about pennies and letting dollars go by the wayside. If you're talking about a \$50 million or \$100 million installation, I don't think anyone in the early stages of design would worry about a \$100,000 computer cost.

Mr. King

At BART we're going to spend about \$200,000 this year on computers to find out what's failed.

When you went through the mathematics, you were looking at averages about failures, either failure rates or mean time between failures and delays. One of the things that I've observed is that

the average failure does not occur during the period of average use, i.e., it does not occur at the average point of the system. I think there are reasons for this, and I'm going to study at BART where these things are actually happening, to see if I can determine what these reasons are. But, in fact, failures occur much more frequently when the system is jampacked even above and beyond the packing that normally occurs because of the increase of equipment utilization.

Dr. Anderson

Anybody else here want to comment on that? I use averages, so I guess maybe I should comment, too. The way I feel, when you start with these problems there is indeed a tremendous level of detail that you can go to. However, it depends on where you are. In your case, in BART, where you really are worried about all the details, that's one thing. When you're in a more conceptual design phase, to get started with a problem you've got to start out with averages. I've seen many instances where people, by doing a lot of work calculating variances before they get averages, actually waste a lot of time. You can often gain a tremendous insight from averaging techniques if you use them properly and don't take them too seriously.

Dr. MacKinnon

We had a discussion yesterday about failure characteristics. One thing we noted was that many failures are nonlinear in nature. In other words, you look at an electronic component, for example, and if you plot failure rate versus voltage on the component, you will find it has a nonlinear characteristic. Also, the spread in the point where the failure occurs may be quite broad. I think this is one reason why they may have problems on BART when the traffic is very heavy. Components in a system such as the wayside BART distribution system would come under a very stressful state at that time; the probability of failures on wayside equipment might then be much higher than would be indicated by greater traffic only.

Comment

Well, in other words you now go to a level of greater sophistication in understanding that failures may be induced by more causes than just increased traffic.

Dr. MacKinnon

That's right. Some of the assumptions we make about the superposition of failure effects may not be valid.

Comment

Leonard was right too when he said that we run around assuming that we've got some exponential probability distributions. I don't think we do.

Dr. Doyon

We may have either an increase or decrease in failure rate, but we should really be talking about times between failure and times to repair.

Dr. Heimann

Again, the discussion of averages. It came out yesterday that probably a very good way of describing availability of the system derives not so much from averages as from the tail of the density function, that is, the probability that a delay of more than a certain amount of time occurs rather than an average, or a variance of that average, using the tail. Has any of these analyses been carried out? Have any analyses been done using, rather than averages, the probability of a delay of more than so many times the tail?

Dr. Doyon

I don't use averages. The process is stationary only if the assumption is valid that the times between failures and times to repair are both exponentially distributed with time, and that's a very, very rare case. It's used only because it's nice and easy to use. But the truth of the matter is, in real life it seldom happens. For example, we know that for repairs we have a lognormal distribution. Many years ago, in testing aboard ship, I

had my own man, who was one of the first to use the MIL-STD-22272M, the predecessor to the MIL-STD-472, aboard ship. We have data to show that if we deleted from the data all accidents, errors, or distractions, the repair time showed a beautiful exponential distribution. As soon as we added to that data the distractions, dropping tools, misleading prints, and all that, we had a lognormal distribution.

Dr. Heimann

I guess that in cases when it's nonexponential it's even more important to look at the tail distribution.

Dr. Doyon

If you find repair time that's truly exponential, it's because the mode of labor involved by the person is almost negligible, like pushing a car, or changing a small piece, or pushing a button; that is exponential because it's almost random in nature. But if it takes any type of human effort of repair where tools are used, then you'll find it's not exponential.

(End of Panel 3 Session)

PANEL 4

USER-MANUFACTURER RELATIONSHIPS

PANEL 4
USER-MANUFACTURER RELATIONSHIPS

The final panel of the workshop opened with an introduction of the panel chairman, Mr. John Marino of TSC, by host Mr. Chan Watt.

Mr. Watt

This morning John Marino is going to lead a panel on User-Manufacturer Relationships, the users being the people actually using AGT systems today, and the manufacturers being those who build them. John Marino is a group leader at Transportation Systems Center, in charge of all TSC programs on automated guideway transit. He has spent five years at the Transportation Systems Center; before that he was with MITRE for five years, and with Boeing, in the aerospace industry, for two years. He has a BS Degree from the University of Detroit, and an MS Degree in Operations Research from George Washington University in Washington, D.C. He is deeply involved in the whole business that we're talking about.

Mr. Marino

Thank you, Chan. On Panel 4 we hope to get at some of the user and manufacturer considerations in this area of AGT service availability. I think we're quite fortunate this morning to have with us representatives from each of the revenue service systems of the GRT type. We have with us Pat Esposito, who is at present an Engineering Scientist with the College of Engineering at West Virginia University, providing systems support and evaluation on the review of the Phase II effort at Morgantown. He headed up the University's evaluation group for the assessment of the Morgantown PRT. During its first year of operations and maintenance testing, he served in various capacities on the Morgantown program. He also has taught in the Industrial Engineering Department at West Virginia University.

Also on the user's side we have Mr. Donald Ochsner, who was introduced to you yesterday. At present he is supervising engineering activities at the AIRTRANS system at Dallas-Fort Worth.

On the manufacturers supply side we have Frank Musil, from the Boeing Company. He joined Boeing's Automated Transportation System program in 1973 at Morgantown. For two years he was design liaison supervisor during construction modifications and system test program of the current three-station system. Prior to that he served in various technical staff capacities on several of Boeing's space activities in the southeastern part of the country.

We also have with us Austin Corbin, Program Manager of AIRTRANS for the Vought Corporation. He has held this position since the award of the contract to Vought, in the summer of 1971, for installation of the system at Dallas-Fort Worth. For a year and a half prior to that he led a special study group investigating people mover requirements and concepts, from which evolved the AIRTRANS design. Before his involvement in transportation, he was Program Manager of several military missile programs, and was the Engineering Manager of a nuclear-powered missile project SLAM. Before coming to Vought in 1960 he worked for GE in the aircraft nuclear propulsion program. He's a graduate of the University of Texas, and he did graduate study at the University of California at Berkeley.

We are also fortunate to have with us Mr. Frank Gunter from Westinghouse. Mr. Gunter received a Bachelor's Degree in Engineering from Auburn University. He spent eight years with the Westinghouse Transportation Division as Program Manager and as a member of its Divisional Staff. He's also Sales Manager there. At present he is located in New York City, and is involved in propulsion equipment, train control, and AGT projects. Prior to that he was with Westinghouse Defense and Space Center for 28 years as Design Engineer and Engineering Manager and Program Manager for Communications and Radar equipment.

TSC has recently been involved in the technical and operational assessment of some of the automated guideway system installations in revenue service. Stan Price of UMTA is going to be doing several more of these operational assessments with various contractor organizations. He has asked TSC to give him assistance, particularly in assessing the AIRTRANS system out of Dallas, the Jet Rail system, the Cabintaxi system, and the VAL system in France. TSC recently has completed a detailed technical and operational assessment of the AIRTRANS system, and a report is available from TSC on that work. If you leave your name and organization with Chan Watt or myself, we'll be happy to send a copy of that report very shortly.

Well, without further delay, I'd like to introduce Pat Esposito, who will talk to us on the experiences at Morgantown, the way they arrived at their definition of availability, and their assessment of how well the system's performing today with respect to that requirement. Don Ochsner will do the same thing on the AIRTRANS program. Then the manufacturers will rebut some statements that the user people will be making, after which we'll turn the tables and do it in reverse. First, Pat Esposito.

Mr. P. Esposito (Morgantown)

As we've heard in the first three panels of this workshop, the subject of service availability for our automated guideway transit has taken on numerous appearances, and by the existence of so many ways of formulating the computation of service ability, the problems of the user and the manufacturer are only compounded. This panel addresses a most important point. However, the other topics that have been discussed are not to be downplayed, by any means. The success of the other topics is very important, because they provide a necessary input to the user and the manufacturer in developing specifications for their systems. The implications and results which must be dealt with on a daily basis are derived from these considerations, and constitute the basic problems of the user and the manufacturer of the transit

system. The significant problem in the specification of system availability for transit systems has been the absence of a measure which is oriented to a passenger's point of view. The passenger standpoint is very important. Passengers could really care less about what causes delays. All they know is that they've been delayed.

The input that I would like to provide you with today is on the Morgantown Group Rapid Transit (MGRT) system, which services Morgantown, West Virginia, as well as West Virginia University. As you're probably aware, the MGRT has been an R&D project under the Urban Mass Transportation Administration. For this system the Boeing Aerospace Company served as System Manager.

A few basics on the system: - The MGRT is a computer-controlled, fully automated transportation system which operates either on a schedule mode or on a demand mode, as passenger rate necessitates. Phase I of the MGRT has been in passenger service since October 1975, and has gone through a year of passenger testing. We've been able to review the system's performance and to assess its compliance with our specifications.

The specifications that were drawn included requirements, characteristics, and goals of the general system as well as of the subsystems. In considering all the requirements, the main points of concern have been the effectiveness measures. Encompassed within these measures, of course, are cost of operating and maintaining the system as well as the level of service performance produced by the system.

The first term which we've defined for the system has been system availability, which is the probability that the system is able to dispatch vehicles on demand. As you note, we define that as summing up the system uptime during a particular time interval and dividing that by the scheduled operating time.

The second term of availability which we define is fleet availability, which is the average fraction of the fleet ready for service. This is computed as a summation of the number of

vehicles that are available in this system's fleet compared to the number of vehicles that are required to serve the passenger demand anticipated.

The third term we are using is trip reliability, which is the probability of successful passenger trips. We define that as the quotient of the number of successful vehicle trips over the number of attempted vehicle trips.

The one measure which we're using to establish system performance is the product of the preceding three. We call it Conveyance Dependability, the product of system availability, fleet availability, and trip reliability.

I think you may be familiar with the first and third terms; the second term, fleet availability, is perhaps a new one that you're being exposed to today. But basically, what we're trying to accomplish by "fleet availability" is the measure of how well the system is capable of supplying the demand that passengers are expecting. To give you a simple example of fleet availability; a system could be available, that is, it could be operational, if you put only one vehicle in the fleet. However, the system would be very minimal with that one vehicle. In the first term, "system availability." this "fleet availability" is not accounted for. So, what has evolved out of our experience has been the second term, fleet availability.

Of course, at this point in the state of the art, there's still no way to be assured that the design will reach the specification on system performance. This statement is especially true of the new systems, which were not installed previously. Second applications, third applications, etc. on systems do increase the probability of compliance with the original specification by the designer of the system.

As an example of this problem, I'd like to direct your attention to a hypothetical specification which says that mean down time should be 15 minutes or less. In this particular case,

it is very difficult to specify tests to guarantee compliance with this requirement. It is still only the best judgment at the design stage of the system development.

Now let us turn our attention back to the service availability, which we have defined as consisting of four terms. It is very worthwhile to set forth common guidelines for specification coverage on the subject of service availability and performance levels. These guidelines would serve to make clear to both the user and the manufacturer what is expected from the system before system construction. To accomplish this goal, all the concerned parties should be involved in developing the guidelines; the government as well as transit investors should participate in this development. Of course, the end result should not be one set of guidelines "cast in concrete." The guidelines should be negotiable by the parties involved in the system construction.

With MGRT we set forth neither the goals for system availability nor trip reliability. However, we did specify that conveyance dependability during the academic year should be 0.967. To arrive at this specification, we naturally had to rely on what levels of system availability and trip reliability could be expected. Using such projections, we were able to set forth specifications for dependability which would guarantee a level of service acceptable to the users. To assess the MGRT's compliance with a conveyance dependability of 0.967, I have to show you a history of our experience. We began passenger service back in October 1975, and are just now completing our initial year of testing. The dependability started out somewhere in the 70-80% range. It has progressed steadily to the present time, at which we are experiencing in the neighborhood of 93-94% dependability. The cumulative dependability level has continued to progress, but again, that is computed from the very first day of passenger service. The fact that MGRT has not met the dependability specification has in no way undermined the need for specifications for this system. We've experienced many days where we've had 100% dependability. However, we have not at this point in time experienced a continual trend of 96-97% or better.

In the original specification development, the specifier and manufacturer engaged in considerable discussion of the dependability specification. Both parties understood the meaning of the specification. However, it was difficult to reach an agreement on this particular specification. Of course, I must emphasize at this point that the MGRT specification was being developed, and the state of the art of transit system service measures was in its infancy. In addition, since it was a research and development project, our problems were only compounded. We were constructing a system and developing a specification after the prototype was service operational. The original requirements for the specification came from our requirements and constraints document for the MGRT. This document established the initial reliability and passenger service levels which must be attained by the system. The MGRT specification evolved from the requirements and the experience.

One point which should be emphasized in future system developments is the preparation of system specifications, and, if possible, better reliability programs. This would definitely aid in the hardware type problems which we've experienced with the MGRT. Since we've had only a single lane in each direction in our system, and a severe failure on the guideways severely affects us as opposed to a bus system, where we could bypass the fault area, we find that our riding public, including the student population, feels very irritated about downtime. Even when the system performs relatively well, with a dependability of 93% or so, we still receive complaints from the customers.

Mr. Marino

Thank you, Pat. Pat will be answering a number of questions during our panel this morning. We do have a large block of time at the end of the presentations for an interaction with the audience and members on the panel. Don Ochsner will now tell us a little bit about some of his experiences and point out some of the deficiencies in the AIRTRANS specification. He will talk about the contractual situation with the system down in Dallas, and discuss some of the problems that he has had to address.

Mr. Ochsner

I have been in the middle of a user/manufacture situation for five of the past six years, and yet, when I sat down to prepare a few notes for this panel, I found myself groping for suggestions or recommendations to pass on to others in similar situations. I decided that the best thing for me to do would be to point out some deficiencies in the AIRTRANS specifications and contractual situation, and discuss some of the problems which developed from those deficiencies.

For those of you who are not familiar with the AIRTRANS specifications, they were drawn up as performance specifications, with a few architectural requirements for vehicle size, brown concrete for the guideway, etc. The system specifications were derived from earlier specifications from SeaTac, Tampa, and tailored for the Dallas-Fort Worth Airport. The system specifications were then integrated with general provisions from the standard construction contracts for other Dallas-Fort Worth contracts. The contract requirements are presented in outline form, with pertinent related comments.

AIRTRANS CONTRACT REQUIREMENTS

- o FIXED PRICE, TURNKEY PROJECT
 - Awarded to Vought Corporation
 - Single contractor responsibility
 - Changes must be fixed-price negotiated
- o CONSTRUCTION CONTRACT GENERAL PROVISIONS
 - Reflected suggested revisions from potential bidders
 - Ambiguity required good relationship between contractor and buyer
- o A TWO-YEAR CONTRACT COMPLETION
 - Not long enough, both knew
 - Expected airport opening to slip

- o DESIGN APPROVAL
 - Went smoothly
- o TESTING WITNESS AND APPROVAL
 - Late in program
 - Mixed up in acceptance
 - Never totally completed
- o TWO-WEEK OPERATIONAL DEMONSTRATION FOR ACCEPTANCE
 - Never done, due to operation of system prior to completion
- o THREE-YEAR MAINTENANCE CONTRACT
 - Vought, almost 2 years
 - RAB since January 1976
- o MTBF AND MTTR RELIABILITY REQUIREMENTS
 - Limited data available
 - Vought extracted early data
 - Not very meaningful to service, but necessary to maintenance

Now I would like to discuss a few of the major pitfalls of the contract I just described, and leave it to Mr. Corbin to talk about some of his suggestions for avoiding these pitfalls.

AIRTRANS CONTRACT PROBLEMS

- o FIXED-PRICE BID TOO LOW
 - RAB knew, Vought knew
 - Vought did not expect as much overrun
- o TWO YEARS NOT ENOUGH TIME
 - Airport opening expected to slip; 6 months was not enough
 - Actually took three-plus years, and today probably four years

- o CONSTRUCTION PROVISIONS NOT SPECIFIC ENOUGH FOR SOPHISTICATED SYSTEM
 - Electrical and control wiring effort huge
 - Field contract administration not used to tight tolerance specifications
- o POLITICAL PRESSURE FORCED SYSTEM UTILIZATION PRIOR TO COMPLETION , WHICH CONFUSED ACCEPTANCE
 - Airport must open with AIRTRANS
 - Vought insisted opening with people support
- o CONTRACTOR COST OVERRUN
 - Became excessive during early operation
 - Financial pressure greatly influenced acceptance
- o EXCESSIVE EARLY MAINTENANCE COSTS
 - Two to three times expected, and affected acceptance
 - Currently running 50% higher than predicted
- o USER REQUIREMENTS CHANGED, BUT NOT INTEGRATED INTO CONTRACT
 - Primarily in utility systems of baggage/mail
 - Third party influenced acceptance because of financial control
- o GENERALLY NEGATIVE PRESS
 - Never gives positive support, even to this day.

I don't know what to do about the negative press. We're still getting it. As recently as a month ago we had another rather bad article in one of the local newspapers. I think we're doing a real good job of serving the public right now, including employees, and the papers still won't leave us alone. So, it was really a rough, rough deal during the first two years.

That's a short summary of what turned out to be a very involved contractual dispute, which in my estimation delayed the further improvement of AIRTRANS approximately a year to a year-and-a-half. I haven't spent too much time determining how the specifications or contract could best be changed. I am prepared to discuss some of these points later on. I do believe, however, that the subject of availability, which we've discussed considerably during the last couple of days, was not the major issue. I also don't think reliability was a major issue. I feel that the financial and political pressures were the controlling factors that caused us to get into the extensive litigation that we're in. And I don't know how to relieve that. You can write better specifications for availability and reliability, but when financial pressures and political pressures get so great, I don't think you can write words that will settle the situation. Thank you.

Mr. Marino

As was mentioned a few minutes ago, we will have time for dialogue. I would like to address some of the questions we've identified from the handout material that Panel 4 would be going over. I would like to ask Frank Musil from Boeing if he'd comment on the early stages of the specification process with the University of West Virginia. I would like him to tell us how much agreement or disagreement there was in the areas of reliability and availability, how he arrived at that definition in the specification, and what the experience has been to date in meeting the requirements. If you'd comment on that, Frank, I'd appreciate it.

Mr. Musil

I think I should give you a little bit of additional background about what Pat has indicated, in that when the Morgantown specification was developed, it was not between Boeing and the University. We, at the time, were building the system in conjunction with UMTA, and were funded directly by UMTA's R&D. Then it was decided to go into this two-phased development

approach, which really has turned out to be a three-phased approach, Phase 1A, Phase 1B, and Phase 2. Both Phase 1A and Phase 1B, which resulted in the current three-station system, were direct contracts with UMTA. Now, the University had worked with UMTA to establish the University's requirements. They, in turn, translated those requirements into a set of requirements with Boeing. An additional complicating factor is the fact that the original specification was between JPL and UMTA, and the Boeing Company, which was to be the contractor at the time, essentially inherited the specification from JPL. The "reliability tree" that Pat showed was used by the Boeing Company to try to establish a prediction of the reliability and availability of the system. There was considerable discretion involved; it was an evolutionary process, not so much, as I recall, to arrive at the definition, which is in the specification, but at the number which the system had to meet.

Pat showed that the system availability, trip reliability, and fleet availability are in the conveyance dependability measure. In our specification, only system availability and trip reliability were specified in the conveyance dependability measure. But the fleet availability measure came after the beginning of the one-year testing period that we're now in, because the fleet size was not what it was expected to be. While it is not a part of our current specification, we'll be in the process of defining a new specification at the University as we go into Phase 2, beginning this week. As a matter of fact, that's why Scotty Davidson could not be here today. He's in the midst of that process. The University does intend to request us to put fleet availability into the availability formulation as a part of the specification for Phase 2. Essentially, the origin of the number for availability came from the University, to UMTA, to JPL, and to Boeing through a fairly long, involved process, and after much discussion about the number. I was not on the program at the time, and I don't know the details of the pressures that pushed the number to 96.7%. I don't think anyone had a rational reason for its being 96.7% as opposed to 97%, or 96%, or 95%; that's one of the

problems with specifying availability. As to how the system is performing with respect to the 96.7% availability, I think Pat indicated that we have a maturing system over this period of a year. Some hardware changes and some software changes have been incorporated in order to achieve the trend of reliability that you see. In addition, there's a part of a learning curve in that also, in learning how to operate the system. It's currently running at about 92%-93% dependability with the fleet size factor included. Now, by including the fleet size factor, the conveyance dependability as compared to the specifications I used has dropped 1-1/2%, so that we're probably running on the order of 94%-95% conveyance dependability if we exclude the fleet availability factor at the present time.

Mr. Marino

Thank you, Frank.

Mr. Esposito

What Frank pointed out regarding the specification is true. The original specification did not include fleet availability. As pointed out, during the progress of the initial operation year, we agreed that fleet size was a contributing factor to the performance that we could expect, and so it was added to the computation of conveyance dependability at that time. Even though it's not in the specifications as a component part of dependability, we have been computing dependability as a function of the three factors, trip reliability, system availability, and fleet availability. And we've actually been comparing that computed value to the specification requirement of 0.967. Basically, the value of 0.967 was evolved along these lines during the initial feasibility study. Considerable thought was given to the passengers' needs, in this case the needs of the students in terms of meeting their classes, as well as serving the general community of Morgantown. Although the dependability number has three significant digits in its numerical value, it basically evolved as a function of the delay time the passengers could tolerate as well as the number of delays that could be tolerated during the year.

Mr. Marino

Thank you, Pat. What I'd like to do now is to address a question to Austin Corbin. Austin, Don has indicated that many of the initial problems of AIRTRANS were due to external forces. I recall that the specification that you had to respond to at AIRTRANS was a very good specification. I think the audience might benefit from hearing about some of the cases in which you and Don had to get together and decide just what did constitute a failure, and what did not constitute a failure. Could you address yourself to some examples of either the adequacy of the specification or the openness of the specification in this area of defining a failure?

Mr. Corbin

I don't think that Don and I agree today on what constitutes a failure. And let me add that Don is one of my closest friends. I've worked with him for six years. The specification was ambiguous in terms of defining what constitutes a failure. There are many failures in the system due to unknown causes. In the aerospace business, your reliability man has to go out and pick up a piece of hardware and say, "Yes, this failed.", and that's a failure. But in the transit system such as AIRTRANS, and I'm sure Morgantown and others, there are many failures for which we never find the cause. I became convinced the conjunction of Venus and Mars causes failures! And even today there are many failures that are not identifiable to the system.

Yet, you can interpret the specifications to say that any time a vehicle stops, that's a failure. But if you can't find out what caused the failure and what caused the vehicle to stop, how can you really call it a failure? So, that's the basic area of disagreement. I think that's going to continue with us unless the owner and contractor agree beforehand what they're going to call it.

I'd like to go on and address another subject. Don mentioned that we had a little disagreement over the specification contract settlement as to whether or not we had achieved the MTBF. Now, the specification has some very ambiguous words, to the extent that

we talk about conditional acceptance and final acceptance. The big issue, one of the big issues in our dispute, as a matter of fact, was whether or not we were to meet the reliability requirements at the time of conditional acceptance or at final acceptance, and really, when conditional acceptance should occur. Actually, during that time period we were taking reliability data ourselves, because we were running and operating the system, taking the reliability data, and keeping it very secret. We wouldn't dare tell Don and his associates what those figures were, because our position was that conditional acceptance had to be given irrespective of what the reliability achievement was at that particular point in time. And, of course, it was all finally resolved by an eventual settlement between lawyers; Don and I really could have settled it long before, but we didn't have the authority to do so.

Mr. Marino

Thank you, Austin. What I'd like to do now is to ask Frank Gunter if he could expand somewhat on what Austin just brought out on this factor of what does constitute acceptance. Frank, I'd like to have you address this question: would it be reasonable, in the area of reliability and availability, to have some kind of a sliding scale requirement? Might there be a reasonable alternative to some of the more fixed requirements in the specification?

Mr. Gunter

Yes. My experience has shown that we have too many contracts for which the basis for acceptance is to be established downstream. We enter into the contract not knowing really who will say it is acceptable or not acceptable. We do not know what test procedures will be used, or what will constitute failure. My own feeling is that, ideally, we ought to have two contracts. The first contract would be to build a system that works, and that for at least one day, meets the performance requirements. The second one would be for a year thereafter, to make it reliable. It is so difficult to anticipate the environment in which you'd be operating. You must have a fundamental

statement of what is acceptable, such as moving a certain number of people per hour, 22 hours of the day. This is something you can measure accurately, and both sides can agree on. But until you can reach such fundamental specifications at the time you negotiate your original contract, I think we're going to suffer from the kind of situation which apparently Don got into.

Mr. Marino

Thank you, Frank. Don, you mentioned in your presentation that if you had to do it over again, there might be some changes you would make in specifications that would lead to fewer misunderstandings between yourself and Vought. What particular area were you thinking about when you made that comment?

Mr. Ochsner

Well, the acceptance criteria would have to be very much like Frank described. I believe we could do a better job at this point in defining availability. During the contractual dispute, we did in fact do that; we rewrote the particular section on reliability to try to take into consideration some of LTV's concerns about identifying failed parts. I think that we really had a compromise reliability section rewritten, but we never did actually turn it over to LTV because of the litigation that was going on. I think that we had the basis of an arrangement such as Frank described. We had identified a sort of conditional acceptance that would have gotten the maintenance effort started, and then, over a three-year period we would have developed the reliability of the system. But the financial pressures and political pressures did not allow us to carry it out.

Mr. Marino

Thank you, Don. Pat, you and Don are representing the user's side on the panel today. One of the things that we often hear about is the cost of maintaining these systems. Could you, Pat, tell us a little bit about one of the current maintenance philosophies that you're using on Morgantown? What part does the University play, and what part is Boeing playing in system maintenance?

Mr. Esposito

Boeing, as the only contractor, was to maintain the system during the first year of passenger testing up until about May 1976. At that time the university staff took over. Of course, they were being trained during the interim period. Since May the University has been operating solely with a small technical representation from Boeing. As far as the Boeing costs are concerned, they are a little higher than we anticipated, but don't appear to be alarming at this point. The figures are approximately 15-25% greater than anticipated, which isn't unreasonable.

Mr. Marino

One point that I think was brought out on one of the earlier panels was that there seem to be more ways than one to address the issue of how to operate and maintain a system such as AIRTRANS, or SeaTac, or Tampa, or Morgantown. To date, with the limited experience that we have with these systems, it seems that two paths are open. I believe that in the Westinghouse case much of the maintenance activity is done on a contractual basis with the supplier, and that at AIRTRANS, and to a degree at Morgantown, a lot of this is performed by the user organization itself. Don, you seem to have been able to pick up the maintenance functions down at AIRTRANS with a smaller labor-intensive force than Vought had been using in performing the maintenance. Can you comment on why that has occurred, and how you do it?

Mr. Ochsner

Well, I think there are probably two reasons why we're able to reduce the number. Probably the single biggest reason is the fact that during the entire contractual dispute, during the time LTV was maintaining the system, they had to retain in readiness the utility vehicle fleet, which we are not using now. In fact, we just have it parked. So, that's another 10 to 12 vehicles that do not have to be maintained at all, as well as a bunch of station equipment and cargo handling equipment which does not have to be maintained. We could not have done it, however,

without hiring maintenance people who were already there working for LTV. LTV has somewhat over 100, 100-120 people, and we cut that down to about 85. And of the 85, we hired 55 of the LTV people, and about 30 were our own staff.

Mr. Marino

In AIRTRANS, how many people are in operations, and how many on maintenance? Can you give us a rough look at that?

Mr. Ochsner

Our maintenance staff, including Supervisor of Maintenance and secretaries and clerks, is 85. We've been running about seven people short of that, or a total of about 78 people on the maintenance staff. In the operations and engineering end, we have a total of 17, of whom 10 are actual console operators. A staff of 85 sounds like a big maintenance staff, but when you divide it by five to cover the three shifts a day, and seven days a week, it doesn't leave you too many people when you spread them out over guideway, electronics, and vehicle maintenance.

Mr. Marino

Frank, could you comment a little bit about the experiences Westinghouse has had performing things on a contractual basis for the airport authorities that Westinghouse has been dealing with?

Mr. Gunter

Well, at both SeaTac and Tampa, our original contract required that Westinghouse perform the maintenance, with a penalty for outage time: in the Tampa case, for the first five years of operation; in the SeaTac case, for the first three years of operation. At Tampa, we have just now negotiated the contract for another five years. Initially, we gave the field team a lot of design engineer support. Basically, the field team amounted to about five people for a system that has 8,000 feet of single guideway and eight vehicles.

At SeaTac a different philosophy was used almost from the outset. Seattle-Tacoma Airport provided us with technicians who actually did the maintenance under the supervision of our people.

They provided us with these technicians at so many dollars an hour. And, depending upon the number of hours we used them, we had to pay for them according to that amount. We had a fixed-price contract, in effect, to do all the maintenance for so many dollars a month. And the only relief we had was an escalation clause.

In the SeaTac case, I believe the three years is up now. SeaTac has taken over the administrative, and practically all of the actual, repair work. I believe the present contract provides one or two men, primarily to be used for diagnostic assistance on system problems. Max, you might have some other comments on that.

Mr. Bitts

Yes, I have. In February of last year, the initial contract was over, and we started a new one with factory technical representatives only. I look at that as the "umbilical cord" to the factory, where all the information is. It also helps us guarantee that we're not violating safety or system integrity. For my part, we will continue to have a Tech Rep as long as we have the system, even if just one. That is because I believe in having an umbilical cord which forces the factory to have another desk on its end, a phone, a man, a file, or somebody constantly ready to support any problem that might occur on the vehicle.

Mr. Gunter

There's certainly that aspect of it. But there's another very homely aspect in having a manufacturer or private agency do the maintenance which we often lose sight of. If a technician down in Tampa wants to buy a resistor, he gets in his car, goes to the local radio shop, and buys it. He doesn't have to put out a requisition, process a lot of paper work, or get multiple bids. There's an ability to react fast in obtaining parts and providing repair. We had problems with the air-conditioning compressor at Tampa. So, we initiated a deal with a local air-conditioning supplier to rework the air conditioners. The contract consisted of fixing them and sending a bill at the end of the month. We have the facility for getting quick turnaround, compensating for

the fact that we didn't buy enough spares of a certain type. This experience compares favorably with the fact that fast reaction is very difficult to achieve when you operate under ground rules of a public authority, particularly when there are restrictions on how much you can buy without going to the board of directors for approval. So there are real advantages of going with contracted maintenance, quite aside from the most important advantage, which is the assignment of responsibility. One man has the job, and he's got to make it work.

Mr. Marino

Thank you, Frank. Don, could you comment on minimizing response time? How is it done at AIRTRANS? Do you feel that you have better control now with your own people?

Mr. Ochsner

Well, the situation's changed drastically since those early times. There were times when we did not get all the information out of LTV when things happened, but that was a long time ago. Now even our unknown failures are very low. I'd say we probably can identify the reason for the problems 95% of the time at this point.

Mr. Marino

Okay. What I am really trying to get at is, when does the clock start if you're trying to compute MTTR? I think that from the user's point of view it starts instantaneously. I also think that from the point of view of whoever is actually doing the maintenance, it really starts when he is notified that a failure has occurred out there. Sometimes that time lag can be either short or long.

Mr. Ochsner

I think perhaps that the notification end is a very minor part. There can be a conflict on the question of when the system is restored. With AIRTRANS, for instance, we have a loop system, and if you get a vehicle stopped, you get several vehicles

crowded up behind it. Our contention was that it's not fully restored until they're all spread out and service is back to normal. I think LTV's feeling at the time was that once the first vehicle is taken out of the way, the system is restored.

Mr. Marino

I'd now like to have the three manufacturers give their presentations, and then after their presentations we still will have something like 45 minutes for discussion.

Mr. Gunter

I'd like to ask a question of both the AIRTRANS and Morgantown people. Based on your experience, would a different system layout have materially improved the availability? Both of you have loop systems rather than the kind of shuttle system that Tampa has.

Mr. Bitts

We've had very good availability at SeaTac, which has a loop system, but a very small one. We might have had a much greater problem in getting good availability, had it been a large system with a larger number of trains on the track. From where you look now, we would have been ahead of the game with some different kind of layout.

Mr. Corbin

Of course we'd have to define availability, and I'm not sure that's been defined properly. That is, if availability means simply that a passenger can get from point A to point B within a specified time, that's different from whether a passenger can get from point A to point B on a specified route in a specified time. Certainly the addition of bypasses and the addition of parallel tracks and additional sidings would help the availability in the first definition, i.e., getting the passenger from point A to point B.

Mr. Marino

Don, why don't you comment?

Mr. Ochsner

I'm not sure that a loop is bad inherently. I think that if we had a chance to do it again, we would have to get in a little earlier than we did. The terminal building design was already there, and so we were restricted in right of way. We considered putting in counter-rotating loops, which would allow a little better redundancy than we have now. That was not possible, because we got in too late, and the terminal building design was already determined. Otherwise, it would have had an enormous impact. I think the loop is acceptable if you get total utilization of the guideway that you have. I think the loop has an awful lot of dead heading back to where you started; it's not necessarily so if you have utilization of the guideway through the entire loop, and redundancy, perhaps, with the counter-rotating loops. Or, in the SeaTac case, they're able to use a shuttle in case they get stopped. Yes, I think the design would be somewhat different. Certainly, if we had been earlier in the game, it would have been different.

Mr. Gunter

I think this is a very good point. We've been reasonably lucky so far in the systems that we've been involved in. We were able to get in at the time of the original building concept, and I think this is a point that can not be emphasized enough.

Mr. Ochsner

I should add that we really were there at the time the building was being built, but at that time the planners were highly interested in small, three- or four-passenger-vehicles, with a thousand of them everywhere. So, they made the guideway about two times as wide as they thought they needed, and it was about three times smaller than it should have been.

Mr. Marino

Frank Musil will now give us some word on Boeing's opinions.

Mr. Musil

I'll try to comment somewhat on those questions that you brought up at the beginning. Being a substitute, I don't have a prepared paper to follow, and so I'll just talk extemporaneously.

In terms of availability and serviceability, the requirements that were imposed on Morgantown system were pretty well summarized by the chart that Pat put on the screen. However, in addition to the 0.967 availability number, the specification also called for a total number of hours downtime which, of course, when considered with the scheduled operating hours, gives you the 0.967 number. But it also called for mean downtime of 30 minutes, which pretty well defines the spectrum, or distribution, of the downtime that you can experience.

In addition to that, we operated in a scheduled mode and in a demand-activated mode. Wait times were also specified, in that the passenger entering the system operating in a scheduled mode should not wait more than five minutes for a car, and a passenger entering in demand mode should not wait longer than two minutes for a car. We do not use a measure of wait time in calculating or assessing the serviceability of the system at the present time. It's very difficult to determine whether or not the person waits more than five minutes for a car. It's compounded by the fact that a person walks onto the platform, and he's allowed five minutes for a car to get there. If the system goes down within a four-minute-and 30-second period, and it goes down for five minutes, of course he exceeds his five-minute wait time by some measure. The Morgantown system is very visible; when the system stops, people quit walking toward the station. And, like Pat says, they start hitchhiking if the cars are not running. So, it's very difficult to determine, on a people-affected basis, how the system is working, because you don't get an accurate count on how many people you affect. This is the major reason we're not using that as an assessment of the system performance.

I noticed that several of the papers that were presented previously had indicated that it was a passenger-delay-hour type of measure which was proposed to be used. I think that in the real world it would be very difficult to assess. You can only assess it in terms of people who show up; you don't know of the ones who are affected before they even get into the station, by hearing about it beforehand.

We also had basic performance requirements in the specification. I notice this symposium, or workshop, is intended to address principally service availability. But when it comes to airplanes, for instance, that the Boeing Company supplies, Boeing does not guarantee a reliability or availability of an airplane to an airline. The company works with airlines to define the cause of airplane misperformance--that it travels at a certain speed and has a certain range, and that it has a certain interchangeability of parts for the different airplane models. But there is no guarantee that an airplane is going to be available at any point in time for use in the airline schedule. Typically, the airplane experience follows the kind of curve that is evident in the Morgantown availability improvement curve. That curve is achieved by learning, and by purchase of improvement kits by airlines. If they discover, for some reason, that either because of maintenance procedures or hardware problems the airplane is not available as often as it should be, they work with the company and develop a kit. The user should realize that there is a maturing of the system after delivery, and that you take account of this, either in the original contract, or by holding back a certain amount of money that will allow the system to be made reliable. Frank broke it down even further than that, into two distinct contracts. I think that this is a valid approach, that you have a period of up to a year before you measure the system availability. It was also indicated yesterday that there are degrees of system development, and that the availability is different for each. The day you open up the system, it's not going to operate at 98% availability. One of the biggest reasons is that, even though you use an analytical model that allocates reliability to

component and subsystem levels, you cannot be certain, without a large test program to verify ahead of time that the reliability of a specific component is achieved, that it is indeed a fact. To look analytically at a component and say--"it has so many bearings which may typically last this long, and it has this kind of sliding circuit, and therefore its mean time between failure in this environment will be so and so."--is often done. However, it's not reasonable to expect that answer to be right.

Also, in real life, you allocate the reliability numbers to the subsystems, and you find that subsystem that gives you the greatest problem is not the one that you thought had to have the MTBF to get you where you are.

Don indicated that political pressure was evident in the AIRTRANS system. Morgantown early in its development was also the victim of political pressures that caused the system to be locked into a design, and developed in a manner which did not permit the testing or the assurance of reliability of subsystems. I speak mainly of the demonstrations of the system which were dictated by the Government shortly before an election.

One of the things which directly affect availability was deleted because of that, namely, the pushing of vehicles. Morgantown had originally intended to have a push capability built in, so that a stalled car could be removed by pushing from the one behind. The development of that technique was time-consuming and expensive, and because of political pressures and funds available, it was decided not to go in that direction. The availability number wasn't changed, but we had to achieve availability by other means.

AIRTRANS indicated that it had neither a clearly stated definition of failures nor a feel for what constitutes acceptance. In the Morgantown specifications we had a quality assurance requirement. The quality assurance section broke down each specific paragraph number in the specification, and indicated how that requirement was to be satisfied in the contract. There were several different ways of satisfying a specific requirement.

Analysis at the critical design review for some of the things which were not testable, or which could be adequately described by analysis, constituted acceptance of that particular requirement. Additional requirements were satisfied by acceptance tests of the vehicle at the manufacturer's site. Those requirements were signed and approved at acceptance test.

Other requirements were specified to be acceptable at conclusion of a specific test associated with the installation and checkout of particular equipment in the field. Special electronics had certain requirements that were satisfied; for instance, the signaling equipment and loop installation that verified that the proper signal was at the proper place at the proper time. This was prearranged, and at the completion of the test the guideway or structure per se was accepted. The system level demonstration was a fourth means of complying with specifications. And this constitutes the things like the longitudinal control system of the vehicle, travel time between stations, the headway interval, and the capabilities to adhere to a certain schedule.

This minimized, but did not eliminate, confrontations between UMTA and the Boeing Company. I might add that the agreement between Boeing and UMTA for the methods of demonstration and the methods of buy-off was completed after a very long and tedious effort.

We intend, in the negotiation at the University for the second phase of the project, that there will also be a Q.A. Section of the specification which is agreed to by both parties, so that every requirement in the specification is verified, either analytically or by test, and the test procedure to be used is also mutually acceptable.

One of the things which appear to be evident, from the discussions in the desire to have a definition of service availability, is the tendency toward the user requiring the manufacturer to guarantee reliability. I think that this is driving, or will drive, the PRT systems, or AGRT systems, or GRT systems into cost positions very difficult to justify. If you assign a

reliability number, and then have to guarantee that number, that implies the need for a tremendous test or analytical program, resulting in a lot of costs that are transferred or passed through the vendors. The way Mr. Smith indicated, in order to get the reliability up, you just go to the vendor and pay to have that done. One of the problems is that you'd like to use off-the-shelf hardware, truck components, automobile components, or whatever. For a Morgantown system, you go out and buy 40 of the components. Say you want to double the mean time between failure of the component. The vendor sells you 40 of them, but he may be selling somebody else several thousand of the same component, and the big customer doesn't care what the mean time between failure is. You have a very difficult time getting a vendor's attention to do something special for you for a 40-lot run when he's selling the things by the thousands to other people. You can talk him into doing it, but the cost that he's going to present to you for that is inordinately large for what you're really buying. The cost is going to escalate quite significantly, and I think far more significantly than Mr. Smith may have indicated yesterday.

Finally, I think that some way of measuring how well a system is doing is certainly called for. There ought to be a pretty concentrated effort at the present time to take the experience of existing systems and find out what the number should be. The definition is one thing, and it's all well and good to define what availability means; however, I feel that the real crux of the matter is the significance of the number from the public use standpoint. I feel, for instance, that in Morgantown, if we were operating the system at 90% availability with all three-minute downtimes, it would be a perfectly acceptable system to the people. If we were operating the system at 98% availability, and the mean downtime was an hour, it wouldn't be as acceptable. So, we see that a number which specifies a service availability, whether it's percentage, or people-impacted, or delay time, doesn't necessarily indicate what the service availability really is in the eyes of the public.

But, on the other hand, it's very difficult to add mean downtime as a requirement, and the real difficult part is to assess the impact of system operation on the public. What will they stand? One of the problems of the PRTs is that we advertise that we're so great; the tolerance of people to downtime thus is not high. A person who waits 15 minutes on an airplane is not nearly so irate as the student at Morgantown who waits three minutes on a car. The percentage of the trip involved certainly is a factor. If he's going on a three-hour trip, 15 minutes doesn't make that much difference. At Morgantown, a five-minute trip and a five-minute wait represents a bad situation, because the students are trying to get to a class five minutes from now.

All of these things certainly need to be taken into account in the definition of availability; stated simply, how do you define how well the system should operate in the eyes of the public?

I think that right now one of the problems is that we are designing systems that have unique applications. In other words, the Morgantown system, or AIRTRANS, is designed for a specific application. I think we'll not make much headway in getting a system availability definition until we develop a set of specifications much as the airlines and the airplane companies do; that is, you get a consensus system performance in terms of headways, speeds, and so forth, that can be applicable in a number of places. We will not be able to continually design a system for Detroit, and a different system for Dallas-Fort Worth, and a different system for another installation. The approach to developing the specification should be primarily between the potential users and the manufacturers. The Government probably ought to take a role similar to that for airplanes - to specify the safety aspect of the system. Make sure that public safety is protected, but let the people who are going to use the system get together and mutually decide what the performance should be, and what the availability of that function should be.

Mr. Marino

Thank you, Frank. We have two more talks from manufacturers, Austin Cobin of Vought and Frank Gunter of Westinghouse; then we'll get into dialogue with the group. So Austin Corbin is going to talk now about some of the findings and some of his considerations from Vought's point of view.

Mr. Corbin

Thank you, John, The day after we were awarded the AIRTRANS contract, I received a telegram from a very good friend of mine, who is an executive with a large New York firm involved in the transportation business. And the telegram went something like this. "Congratulations for winning AIRTRANS. Your first act should be to initiate legal action against all your subcontractors and against your customers!" Well, that really isn't the kind of business we want to be in. It isn't the kind of business that's going to make AGT systems viable. Unfortunately, it's the kind of business that we've all been in.

Now, I'm going to speak on a general basis today, and put some unrelated thoughts together, all aimed at one objective that I hope you will carry away with you, so that we can all make AGT systems viable. I think there exist factors that might make the entire AGT concept go completely "down the drain," and cause people to forget it evermore. They have to do with the nature of the contract, the nature of performance requirements, and how we do our business. I think they're very important. I've lived with them for the past five or six years.

I reviewed this presentation with my management prior to coming up. And they said, "You're being a little hard, aren't you?" I said, "Well, perhaps I am, but it happened at BART, at AIRTRANS, and at Morgantown, and Westinghouse has had problems. I think it will happen again if they're not careful. This is the kind of group that can prevent it from happening."

I want to talk about performance. I don't think MTBF or MTTR are adequate measures for performance systems. These were performance requirements spelled out in the AIRTRANS specification. As Don Ochsner mentioned, they were very carefully thought out and well prepared. The specification gave a vehicle MTBF of 500 hours per vehicle, a 30-minute MTTR, and 30 minutes to restore. On the face of it, one passenger vehicle would fail every 9-1/2 hours, and you have 30 minutes to restore it. So, if you meet that requirement, you're free and clear if we can tolerate a system that has a vehicle fail every 9-1/2 hours and takes 30 minutes to restore!

I've seen here at least two of our colleagues show graphs of life cycle cost versus MTBF. This looks very good, I admit, but I don't know where the minimum part of that curve is, and I don't think anybody here can predict the minimum part of a curve for a new system.

Let me inform you that MTBF and MTTR are not currently being taken on the AIRTRANS system. I mentioned earlier that we took it secretly for a two-week period, during litigation, and made some of that information available to people at TSC. But today we don't know what the MTBF and MTTR of the AIRTRANS system are. Why don't we take that information, interpret it, and present it for use? The airport can't afford it, because it's going to increase the cost of its maintenance. Vought, as an organization, would very much like to have it, but we can't afford to do it, because this kind of money would have to come out of our pockets. So, the truth about these numbers is that we may not be able to measure them unless we got a sizable amount of money. I don't know many transit systems today with this kind of money.

I said this before, and I want to say it again, the unrealistic requirements for mean time between failure put into a contract can help make AGT systems go "down the drain" as a means of transportation. Now, with that reaction you'll probably say "Ah, he's involved and they can't meet this kind of requirement." Well, we can meet it. We made extremely reliable missiles. How

do we do it? We go right back to the manufacturer and impose strict manufacturing and quality controls, which cost money. I don't believe that transportation systems can afford that kind of cost. Think very carefully before you impose a requirement that can't be met.

What is important at this conference is the subject of availability. The public doesn't really care about MTBF. The AIRTRANS can fail and be restored, and the passenger won't even know about it. It happens very often. So, availability, which is a measure of how you get to where you want to go from where you are, is the only thing of interest to the passenger. But to the owner of the system, the significant factor is maintenance cost, and maintenance cost can be tied back to reliability only partly, because what you're really after are those things that cause you a high maintenance cost. During the year and a half that we were maintaining and operating the AIRTRANS system, we had an active program of identifying the maintenance cost items. We were constantly reviewing that list, not just the items that had the most failures, but the entire complement of maintenance cost items. This was a program that went on for a year and a half. Hopefully, it has resulted in a low-operation and maintenance cost for AIRTRANS. That is not a reliability program. All this time we didn't know what the reliability was.

So, I think it's very important that performance requirements be limited to criteria of availability and low maintenance cost. Forget about MTBF and MTTR in your contract and in your specification. A good manufacturer is going to be concerned himself with these things.

I'm going to divert just a bit now, and get away from this issue. I think it all gets back to the same thing, though. I'm touching, incidentally, on many of the things that are included in the TSC AIRTRANS assessment report. That report was an independent assessment by the people at TSC, and involved about twenty people. They came down to criticize and evaluate Don Ochsner and me and our people. I think they did a remarkably good job, and the discussion brought out many good points.

This is the problem of acceptance which has also been a problem to all of us who manufacture hardware. I think it was said earlier, and I would like to repeat, there is going to be a long period of trying to improve performance. In any system you're going to have gradually improving performance until you get to that stage where you can call it a mature system. The Department of Defense doesn't ask for a firm fixed price on open-bid contracts with performance guarantees on any new aircraft, nor do the airlines when they're buying new commercial vehicles.

In the meantime, we have to start our new service; we're going to start hauling passengers on that new immature system. So, you've got to have a contract of some sort to provide for this interim period when you're going to be carrying passengers, and you're going to get bad publicity. It happened at Morgantown, and it happened at AIRTRANS. The only way out is a three-phase contract, which was mentioned by one of my colleagues. And we didn't discuss our presentation prior to this meeting. One contract provides the hardware; for this case you can make a certain commitment for time, money, and schedules. Then you've got a period within which to make the immature system mature, and that has to involve a new contract, and a new opportunity to gain or lose money. Finally, you have a period of maintenance for that mature system.

As I said earlier, any new service is going to start as soon as construction's done and operation has achieved a certain level of dependability. There are going to be social and political pressures to put the system into service. Any system is going to start revenue service as an immature system, regardless of what anybody writes in the contract, and regardless of what the plan is. I think a good PR campaign is important. We had a very poor PR campaign in Dallas-Fort Worth. Our worst press was dealt us by one of our local television stations. Everyone in the area came to see AIRTRANS and complimented it, except one of our local TV stations, and it did us a great deal of harm.

I have some thoughts on construction and maintenance. I think that you're going to have to perform maintenance in the early phase with the engineers and the designers, because these are the people who understand why it works and why it doesn't. If it doesn't work this way, what change have I got to provide to make it work? We didn't do it enough, but we will in the future. The initial maintenance has got to be performed with the same kind of competence that built the system, although you can gradually phase from your skilled engineers to your skilled technicians. And at a point in time you can turn that over to the most skilled and best trained people to run it as a mature transit system. Again, I suggest that you get a three-phase contract.

Mr. Marino

Thank you, Austin. Frank Gunter will be our next speaker. He will discuss manufacturers' responsibilities.

Mr. Gunter (Westinghouse)

Thank you very much, John. I'd like to follow the outline that John suggested by asking panel members several questions. The first of these relates to the kind of specification for availability requirements that have applied to systems in the past.

We've been involved in many types of availability specifications during the past three years. Some were applicable to AGT systems directly, and some were applicable to other transit systems. The three general categories pretty much illustrate the spread of these:

a. "Make it Work" Approach

At the Tampa airport, the original contract for the AGT system included the responsibility for maintenance of the equipment for the first five years of revenue service. There was no warranty obligation in the contract; instead, there was a liquidated damage clause which said that if the system was not available to carry passengers from the landside building to the airside building cumulatively 710 out of 720 hours a month,

we had to pay. I think for the purposes of this discussion I'd like to call this approach the "make it work" approach. We think this approach made a lot of sense. There was a clear definition in the original contract as to what availability we had to achieve. Total outage time for new cars that prevented a passenger from moving on the system more than ten hours a month resulted in our having to pay a liquidated damage amount which was also specified in the contract. If you figure this out, this turns out to 98.6% availability. This availability was related to the customer, but actually, it was expressed in terms of equipment availability. We had to meet this requirement whether or not there was a customer there.

b. "Sudden Death" Approach

Another category, such as NYCTA uses, is a kind of what I call the "sudden death" approach to establishing requirement for availability. On a new car that it buys, the Authority requires that an eight-car train run 30 days in revenue service without a failure. Until such time as your eight-car train can run 30 days in revenue service without a failure, you don't get paid. They then add a warranty requirement for two to five years to repair and replace failed parts that happen on the system. Beyond that, they have a not particularly acceptable practice, from the standpoint of a manufacturer, of withholding funds until modifications are made which ultimately provide acceptable reliability levels. The worst part of it, though, is that "sudden death," 30-day test.

c. "Classical Approach"

Other users that we've talked to took the kind of classical approach requiring preliminary and final MTBF and MTTR analyses, requiring that these be submitted for approval, requiring performance monitoring by a third party for a specified period such as a year, requiring the contractor at the end of that period to make such modifications as were necessary to achieve the availability and reliability and mean-time-to-restore requirements, plus a warranty clause.

Too often, unfortunately, acceptable levels of performance and the test procedures to be used in measuring these things are not specified at the outset. And you really end up with the kind of situation which I label, "Buy now, hassle later" approach to availability.

The second question I'd like to address is the extent to which there has been agreement or disagreement on specifications between the user or specifier and the manufacturer in the availability area. There is seldom any apparent disagreement on the availability specification at the time of bidding. However, unless these specifications are explicit as to how availability will be measured and exactly how it will be monitored, the conditions under which the monitoring takes place, the responsibility for maintenance, and the procedures to be used for defining and evaluating failure procedures, we're really opening the door for possible problems in the future. Without such explicit specifications, a manufacturer in a competitive bidding situation will usually take his more favorable, that is, the lower cost, interpretation of the requirements.

Then there's a second problem, that often the specifier doesn't represent what the user has in mind. And when this happens, then you really have hassles later on.

The third question seeks for examples of user-manufacturer misunderstanding which ultimately lead to trouble. Well, the first one is really the difference in the meaning of availability. To users, availability means the capacity of moving people between desired points on the schedule you had in mind. To the specifier, availability usually means a formula involving MTBF and MTTR. To a manufacturer availability usually means he has assumed the responsibility, shared with others over whom he doesn't have any control.

The second area which has caused trouble in the past is the failure to define the maintenance concepts early in the game. The organization to be used, the training to be used, the stocking of parts, the assignment of responsibilities, test equipment, and

facilities are too often not spelled out until long after the contract has been let, sometimes not until after the equipment is delivered; and so, too often you end up with designs which are not compatible with the maintenance organization that you have established.

Finally, we must include the failure to answer at the time of request for proposal, the key questions which we discussed here earlier today. What constitutes a failure? How do we minimize the effect of a failed subsystem on the balance of the subsystems? Who will take what availability data? How will it be evaluated? These kinds of key questions should be spelled out at the time the request for proposal is put out. What changes in specifications would we recommend? We believe, first, that test procedures and criteria for acceptance of availability data should be included in the initial request for quotation.

Let me demonstrate a very good example of a procedure that makes sense to us. We had a requirement at Tampa to show that we could carry 84 people per minute between the landside building and the airside building. We asked, and this was settled in the preliminary stages, how this was to be measured. Where could we get the people? There are so many above 60; there are so many below four years of age. And we are to have those people there, and they're to climb on the system, and we're to count them. Well, we agreed to this, not realizing what we were getting into. When it finally came to the date to see if we met this requirement, where were we to get 350 people, which is really what we wanted to demonstrate the ability to unload a 747 in about 3-1/2 minutes? We were stuck.

One of our technicians, who was a local product, claimed to have a solution. "We organized a Crusade for Christ that we're going to have out at the stadium in a couple of weeks, and we're running short of money to pay for expenses of some of the people we're bringing in. If you will give us \$2,000 for our Crusade for Christ, I'll get you 340 people of the right mix. So, the following week, in six pulpits around town, the announcement

was made by the preacher that on the following Saturday they would like to have 60 volunteers, so many to be above 60, and so many to be below four years of age, and they were all to go out to the airport to see the new airport and ride on the new transit system. Well, sure enough, at 10:00 o'clock on Saturday morning, six buses, each with about 60 people in them, showed up. We brought them up, we briefed them, and they had a ball. We ran our test, and we were a little squeamish as to whether we were going to make it or not; so we arranged a nice buffet spread for them. They sat and ate while we went over the data to see if we had to rerun the test. Here was a case, though, where there was a very explicit procedure established; there was no question. All you had to do was sit there with a counter and find out if the number of people could ride that system that the specification required during the time required. This is the sort of thing that we think has to be done in the future. Maybe a stop-watch measurement of the arrival time of vehicle as compared to scheduled would be appropriate. But it ought to be spelled out. A daily schedule of vehicle runs ought to be included, perhaps. And the test should be to see if the vehicles make the schedule.

Second, make sure that the test procedures and acceptance criteria are directly relatable to the users' people mover requirements. It would make no sense at all to the 50-second ride which we have in Tampa to set up a category that said that if they arrive within three minutes, it's acceptable. It should be related to what the user's people mover requirements are. The requirement at Tampa was to make the plane-- to be able to transfer from one flight to another within the time allowed by the schedule between planes where transfers were allowed.

The next point I can't stress enough. Allow adequate time for acceptance testing before liquidated damages for delay and other penalties are assessed. Now, the best way I know to do that is to place the order for the people mover system about the time you place the order for the civil construction, and not to wait for two years. Too often people have waited until the civil construction is well underway before they get around to doing

anything about the people mover system, not realizing that the construction at the site will be maybe equally long, or longer. But second, let's have a reasonable time before you start penalizing us for liquidated damages, because you end up with a hassle over who did what to whom at a time when you should be working together solving problems.

And finally, allow the manufacturer to choose how he will design the system to meet the requirements. Don't put too many constraints on him. Don't decide where the guideway has got to run before you come talk to him. Don't decide that there shall be no sidings until you've had a chance to talk to him.

We recommend the following approaches to improve future system availability:

1. Provide more planning in the system layout and design to minimize the impact of failures.
2. Furnish sidings for disabled vehicles.
3. Adopt a recovery concept. For example, decide how to recover a vehicle early in the game, and stick to it. At Tampa, we decided not to recover vehicles, because we didn't feel they'd be needed. There is a redundant system there, i.e., every path has two separate guideways capable of independent operation. At SeaTac we had a recovery problem. We had a recovery vehicle there, a battery-powered-mine locomotive which we equipped very inexpensively to go out and haul in vehicles, to get them out of the system. At the same time, at SeaTac we had the ability to operate a shuttle around a vehicle stalled between stations. Redundant paths should definitely be considered. The environment in which the vehicle operates is more severe than that in which the wayside and station equipment always operate. We're apt to get failures on vehicles. If they block the vehicle behind them, we're in trouble.
4. The location of maintenance facilities is very important. The choice of location can often make a tremendous difference in

the mean time to restore. If the maintenance man is required to walk out to the vehicle, you ought to have the facility located centrally with respect to all the vehicle paths.

5. Provide an emergency exit, a walkway alongside the guideway on which people can get out of the vehicle. We don't recommend that you get out of the vehicle unless there's a fire; nevertheless, the time will come when you might have to get out of the vehicle. We've run into some interesting solutions to the problem. Down at Williamsburg, on the Busch Gardens system, where they have quite high elevated structures in some places, we recommended very strongly that they put in a walkway, so that people could get out of the vehicle and proceed on foot. They decided not to. And their solution, I think, may be a very satisfactory one. Every time a vehicle is stalled and they want to get the people out of it, they're going to call the fire department to put up a ladder! That's a very simple approach. We've recommended for other locations, where they don't want to put up a walkway for aesthetic reasons, that they buy one of these little trucks such as the airports use that have the stairs on the back, and drive it over and recover the people out of the vehicle.

6. During pre-revenue operations, and during warranty periods, if there are any, the failure reporting system should be set up, operated, and changed, if necessary, so that it reflects the data not only to tell you what hardware failed (which is the way most of them are organized), but also to permit you to find out whether the contractual requirements were met.

7. Spare parts ought to be acquired. We have a chance to develop a listing to buy and know what spare parts are to be bought during this pre-revenue, or the earlier revenue, operation. Too often no action is taken to procure spares until after the maintenance is taken over by someone else. Usually we found that the reserve stock that we've had for the warranty period is the thing that saves the day, but you can't always count on them.

8. Diagnostic test equipment should be used during the pre-revenue period, and during the early revenue period.

9. There should be an easy way to assure that change pages will be inserted in instruction books by people who need to know of these changes. This is one of the most serious problems that I have seen in field maintenance. We make a change in the field, change the instruction book, issue a change page in the instruction book, and it ends up in a file cabinet somewhere. A year later we realize that the device doesn't correspond to our drawings. These are simple things, but they make an awful lot of difference in mean time to restore.

10. Finally, the user should expect that some items important to availability will be missed in the initial contract, and should be prepared to pay to have them corrected.

We recommend very strongly that the industry consider the practice used at Tampa and SeaTac of having the manufacturer take responsibility for three-to-five-year maintenance as a part of the signed contract, with specified penalties for unacceptable availability. In other words, tell the manufacturer, "Make it work."

Mr. Marino

That concludes the formal presentations by the members of the panel. Now I'd like to open the panel to questions from the audience.

Mr. S. Spinweber (Port Authority, N.Y. and N.J.)

I'd like to ask Mr. Corbin a question. I wonder, Austin, if LTV had built a full-scale prototype test track, would that have solved many of the problems you had? How much would that have helped you?

Mr. Corbin

As a matter of fact, in our initial planning for the AIRTRANS program we did have a test track planned as part of the entire program. We deleted it because of two things: first, because of the time element - a two-year contract made it impractical;

and secondly, because we had a firm fixed-price contract, and it was money that apparently did not have to be spent. Would it have been useful? I think if you ask people who have been associated with AIRTRANS for the past five years, you'll get a difference of opinion. So, the answer I'll give you is my own opinion, which does not necessarily reflect the opinions of the various people who were involved. There would have been some benefit, although I can't guarantee that. But as to whether the test track would have answered most of the questions that later caused us to make changes, I do not believe that it would have done so. As I said in my discussion a while ago, I think there is a vast step from a beautifully running test track to an operational system.

Mr. Spinweber

I understand that, but I think it's a bigger step to go from a paper design to a revenue system without going through some kind of testing steps.

Mr. Corbin

If you have the time, it certainly helps. But let me bring to your attention the fact that most test tracks just can't incorporate all the things that you have in an operational system. In the case of the airport, the sharp curves, the frequent stops, and the grades would make it very expensive for test tracks to be completely representative of the two loops at the airport.

Mr. Spinweber

There's one way to get around that, and that is to build the prototype as a portion of the final system.

Mr. Corbin

That was really the basic element of our plan. We intended to do our early initial testing on what is known as the two-loop area. We intended to do our design proof testing in that area, but unfortunately, construction delays made us get into that area about six months late.

Mr. Spinweber

May I ask Don the same question? Would you ever buy a \$19 million or \$20 million system again without a planned prototype and a full-scale test track?

Mr. Ochsner

I have no disagreements with Austin on this point. The two-year contract didn't allow for that. It depends on the complexity of the system, too. They had planned to run in one loop, which would give you vehicle miles, but nothing like the day-to-day operation. You just can't get the mileage to wear out the parts and check out the control system. You also would have very little switching, whereas AIRTRANS does a lot of switching, and a few door operations, but nothing compared to the entire system. It's a big step from these operations to the total system operation. I think that if you have the time, you ought to do as much testing as possible. However, if the testing conditions don't closely approximate the actual conditions anticipated, the test results could vary greatly from the actual conditions later encountered.

Mr. Musil

I'd like to comment that we do have a full-scale test track in Seattle for the Morgantown system. The test track reproduces the rail configurations, has all of the speed transitions, the speed levels, the switches, the turn radii, the stopping positions, and the same control system as the Morgantown track. Now, it has proved beneficial, but there's also an awful lot that gets by that test track, because it does not have, for instance, a 10% grade, as we do in Morgantown. It's a different atmosphere from Morgantown. If the test track has included a 10% grade portion such as we have in Morgantown, we would have gotten a lot more data. For instance, in the ride comfort area, the Morgantown vehicle steers off a rail. The installation of that rail itself is very good when accurately controlled on a relatively small test track. However, in the construction of the Morgantown guideway, the installation of the steering wheel is not quite

as good. And while the vehicle has excellent lateral ride characteristics at the Seattle test track, there are spots on the Morgantown test track where it is not so good, because of the difference in construction. It's very useful for getting a vehicle in reasonable operating shape before you ship it to the operating site; it serves as an acceptance test for the vehicle. It can also be used, and has been used, for some endurance testing. But still, the surface condition of the track, the exact condition of the rail as installed, does not exactly simulate the environment as it is in Morgantown. So there are wear-related things and endurance-related things that I don't think you would ever find at the test track. Nevertheless, I think it is really helpful.

Mr. Spinweber

You're talking about engineering testing under controlled conditions, but I'm talking about full-scale prototype on the site as part of the system.

Mr. Musil

Yes, there's a big difference. But even the test track that we have has been a benefit.

Mr. Spinweber

Not as much as it would be if it was on location.

Mr. Musil

Right. At Morgantown the final vehicle was a different design. The first phase, Phase 1A, was a prototype evaluation phase; those four and five cars did operate on the actual environment.

Mr. Spinweber

But that had a meager impact on the design?

Mr. Musil

Well, the car was completely redesigned because of that.

Mr. Smith

I'd like to introduce an additional issue at this point, and then ask the panel for their comments. The Department of

Transportation is sponsoring quite a bit of work in system availability right now. Let's assume this has some result in the next year or two. And let's assume that we reconvene next year some place, that we've got models, and that we translate these into hardware requirements. We can look at the performance from the passenger's standpoint, the operator's standpoint, and the manufacturer's standpoint. Now, you want to buy a system. To what extent are suppliers at the subsystem level really able to say that the risk involved in expecting this system to work according to specification is reasonable or unreasonable? That's the first part of the question. To what extent are they prepared, and if they're not prepared, what can DOT do about it?

Mr. Marino

Many of these systems are not really well known to the urban planning community. The urban planning community has a set of procedures and tools that it uses to analyze conventional transit systems. We in DOT, and in Dr. MacKinnon's System Operations Studies in particular, are developing a set of models both of the planning variety and the more detailed variety that are specifically being constructed, to be made available to and used by the planning community. Right now, if someone were to try to come to grips with availability for the downtown people mover project in City X, I don't think he would have any tools available to trade off the type of service this kind of system can provide against something else. So, tool development, with training of planning people to use the tools, will help one to come to grips with some of that problem area.

We also have underway activity in definition standardization that may well result in a consensus opinion that maybe there isn't the need for a single definition or a single number. Perhaps, for a given application or system concept, one approach should be used. For another application, perhaps we should use a different definition with less stringent quantitative requirements.

Mr. Smith

Assume, John, that all the people in this room agreed on quantifying requirements, and that the manufacturer writes a very quantitative specification. He then approaches a supplier and asks for a certain type of wheels, and for particular brakes which meet special requirements. To what extent can the supplier convince the potential buyer that he knows how to deal with these requests? What data does he have available? Does he have data such as failure rates, etc.? What are the plans of the Federal Government to improve the situation?

Mr. Marino

At the moment we are assessing Morgantown and AIRTRANS, and obtaining reliability data from each. It's obvious, from some data that we recently reviewed, that the system isn't always at fault for the vehicle not making the trip in its assigned time. One has to compensate for the environment that the vehicle operates in when one is assessing availability measurements. Weather and passenger intervention can both affect system operation.

(Note: Two comments followed in answer to the immediate questioning, both with relation to Morgantown's reaction to downtime.)

Comment 1

On the Morgantown system we had problems of the type suggested here, not actually system failures, but events that nevertheless resulted in downtime. One such example is the holding of doors by people. The data that you saw included all those downtime events that are not system failures in themselves. We have suggested sort of a pragmatic approach to discount these typical incidents which affect downtime. In a sense, we cut the time in half from the calculation, and then label it "an act of God".

Comment 2

Well, in Morgantown, unless the system is inhibited from dispatching a vehicle completely, there is no downtime associated, and hence no change in the measure of our availability, since availability is related to the downtime. In other words, if we're operating on a schedule, and there's supposed to be a dispatch of three vehicles every five minutes out of the station, then if we get three out in six minutes, that's not counted as downtime in the Morgantown system. We do, however, have a measure of incidental downtime. Suppose, for example, that an FSK message traffic from the vehicle to the computer commands a door to close. If it doesn't close, a door close failure is reported back. A record of all the door close failures is kept throughout the day, so that you can go back and count, if you really want to, the number of door close failures that are associated with passengers holding the door open.

Mr. Sadowsky

I'd like to carry this one step further with Frank Smith on the general theme concerning the reliability program requirements in building transit systems. There are certain costs necessary in building high-reliability systems, and after the systems are built it's difficult to retrofit reliability into them. On the other hand, it is necessary beforehand to identify the costs of reliability and put them into the program rather than to wait until a system has been built and then retrofit and put mod packages in. That's a costly way of achieving reliability. So we must try to define the reliability requirement and the associated cost of a total reliability package. This goes down not only to major prime system areas, but also to the component and subsystem levels. The cost of reliability should be defined ahead of time, so that you will know what you're getting for your money. There are things that are cost effective in reliability programs, and things that are not. Programs should concentrate on those things that have a direct impact on the design, development, and the procurement of high-reliability equipment.

Mr. Reed Winslow (MITRE Corporation)

For the past three days we've been talking about three different measures of availability: (1) as seen by the passenger; (2) with respect to system operation; and (3) as a requirement in the design and engineering of the system. They are all necessary and different, and we can't ask for one without needing the others. Mr Corbin hinted at some of this when he was talking. I think, however, that even though we must recognize the importance of operating criteria as well as the need for accommodation of the user, it ultimately becomes necessary for the manufacturer to come up with a set of MTBFs and MTTRs, or some substitutes for them, in order to design, make tradeoffs, and develop the system.

The difficulty, I think, comes about in the form of contract we use. If you're going to write a specification to procure a vehicle in terms of subsystems and components, vehicle guideway, and so forth, then the system manager must specify those things. If you're going to let a turnkey, fixed-price contract for a designer and constructor, then you should not specify those things to him; rather, you should give him the goals that he's expected to meet on the other two criteria, and allow him to work those things out. If you do that, then the manufacturer has to accept the responsibility for bringing the system in, finding out whether it meets those criteria, and modifying it at his own expense under the fixed-price contract to bring it up to the level of the contract. Basically, a manufacturer who takes this fixed-price turnkey type job should bear the responsibilities involved. I wonder if any of the manufacturers would care to react to that.

Comment from Audience

I'd like to comment on that. I agree with your approach, but the contract must certainly be presented to include definite, measurable performance criteria, so that both parties know exactly what they're talking about. Too often our contract calls for data to be tested in accordance with specifications to be prepared in the future and approved by the engineer, and then the data will

be considered acceptable if the engineer approves it. This type of approach is too highly subjective. On the other hand, if the test procedure itself would be spelled out in the RFP, and the statement of what data is acceptable and what data is not acceptable spelled out in the contract, I think there is a reasonable basis for a fixed-price contract with the responsibilities that you suggest.

Comment from Audience

We did one big contract under a fixed-price arrangement, as Austin did at LTV. I think Austin's comment is quite appropriate that the manufacturer is entitled to a reasonable profit. Signing up with a fixed-price contract with nothing but penalty clauses, which is what Jerry's suggesting, and Westinghouse has indicated it's under, does not seem to me to be a fair arrangement. As for the "other side of the coin" on this matter, what are the incentives and the possibilities for increased profit for the manufacturer if he does a good job? I think Dr. Doyon mentioned that you should give the manufacturer incentives.

Mr. Chan Watt (TSC)

To follow up on Frank Smith's question on what DOT is doing about reliability data, what do the manufacturers feel that the DOT ought to do toward making failure rate and MTBF information available for transit designers' use? MIL-HBK-217 and other compilations of failure rate data on electronic parts have been around a long time. Is there a need for a similar compilation of failure data on transit-related parts?

Mr. Gunter

I think there certainly is a need for it. One of the big problems we have had in predictions we've made is that everyone says MIL-HBK-217 is the final authority; still, to decide what severity factors you should apply to the data in there is a big

question mark. I know that in several cases we used military jeep-type environment, figuring it was rough enough for a smooth-riding transit system, but it turned out to be completely inadequate. So, a new MIL-HBK-217 for the transit industry might be a worthwhile project.

(End of Panel 4 Session)

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