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THE DEVELOPMENT OF MEASURES OF SERVICE AVAILABILITY

Volume III: Application Guideline Manual

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16. Abstract

Service availability is defined as the impingement of failures on passenger perceived service. The alternate technologies and applications for Automated Guideway Transit (AGT) systems require service availability measures (SAMs) to gage the impact of alternate reliability and maintainability (R/M) options and goals. The transit industry views various forms of passenger delay potential to be the appropriate parameters of service availability. The propensity of a system to induce delays is a complex function of R/M and operational characteristics. No single measure or model exists which can be uniformly applied to different technologies or applications. A methodology is presented to compute these relationships for simple loop and/or shuttle systems. More complex systems will require computer simulation procedures.

This is the third of three volumes. Volume I is a summary of the research effort and results. Volume II is a compilation of all Interim Reports submitted during this project.

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PREFACE

This three-volume set of reports constitutes the Final Report on the project "The Development of Measures of Service Availability". The project was conducted for the Transportation Systems Center (TSC) and is a part of the Urban Mass Transportation Administration's (UMTA's) "Automated Guideway Transit Technology (AFTT)" program. The objective of the project was to develop passenger-oriented measures of service availability which could be used to control the level of service provided by AGT systems throughout their life cycle.

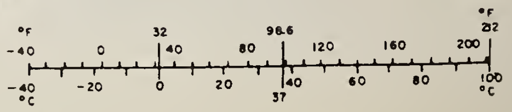
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

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

Approximate Conversions from Metric Measures

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



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LIST OF ABBREVIATIONS, SYMBOLS, AND SPECIAL TERMS

α - Dummy variable computed to simplify station delay calculation in short-cut method

λ - Failure rate, number of failures divided by operating time

AGT - Automated guideway transit

Buyer - General term designating procurement and operating agency, including consultants in support of such agencies

CH - Cushion Headway, difference between normal time spacing of vehicles and minimum spacing allowed by safety and/or operating constraints

C_v - Vehicle capacity

D - Cumulative delay incurred by delayed passengers due to a failure or combination of failures

D* - Cumulative delay incurred by delayed passengers due to a unit failure

$\overline{D}$ - Average delay per delayed passenger

$\overline{D}_v$ - Average delay per delayed vehicle

DPM - Downtown people mover

DR - Total system demand rate. Passenger trips per unit time

EC_a - Average excess capacity available at any given station to dissipate queues subsequent to a failure

EC_n - Normal excess capacity. Available system capacity in excess of that required to meet passenger demands during normal (unfailed) operation

ED - Expected delay, average delay on an average trip

FMDEA - Failure mode and delay effect analysis

LF - Load factor. Measure of vehicle utilization equal to number of passengers on board divided by vehicle capacity

LOS - Level of service

LR - Link flow rate, passengers per unit time traversing link

MTBF - (Mean-Time-Between Failure). Measure of failure frequency equal to the operating time divided by number of failures observed

MTTR - (Mean-Time-To-Restore). Measure of maintainability, in this report, MTTR is the mean duration of a failure

N_f - Number of vehicles operable during a failure

N_n - Number of vehicles normally in operation

N_r - Number of vehicles operating during service restoration subsequent to a failure. Applicable if excess capacity is derived from inserting extra vehicles into the system

N_s - Number of vehicles stopped due to failure in system which permit headway closure

PD - Number of passengers delayed due to a failure or combination of failures

PD* - Number of passengers delayed due to a unit failure

Pr_d - Probability of delay, likelihood of experiencing a failure induced delay on an average trip

RFP - Request for proposal

SAM - Service availability measure

Service Availability - Impingement of system failures on transportation service as perceived by passenger

SRT - Service restore time. Time interval following TTR required to dissipate station queues to normal values

Supplier - General term designating manufacturers, contractors, consultants, etc., engaged in design, construction, manufacture of AGT systems

TT - En route time for average trip

TTR - Time to restore for a specific failure

$\overline{TTR}$ - Mean time to restore

$\widetilde{TTR}$ - Quadratic mean time to restore (RMS value of all TTR values)

V_f - Vehicle velocity during a failure

V_n - Normal vehicle velocity (average)

V_r - Vehicle velocity during service restoration. Applicable if excess capacity is derived from increasing vehicle speed (average)

1. INTRODUCTION

This document is the third of a three volume set which, collectively, constitutes the Final Report on a project conducted for the Transportation Systems Center (TSC) as part of Urban Mass Transportation Administration's (UMTA's) Automated Guideway Transit Technology (AGTT) program. The objective of the project was to develop passenger oriented measures of service availability which could be used to control the level of service provided by AGT systems throughout their life cycle.

Volume I of this report presents a summary of the research tasks and findings. Volume II is a compilation of all Task Reports submitted during the project; hence, it contains the details of the research effort.

This document presents guidelines for the establishment and control of service availability during the planning, procurement, and operational phases of an AGT system. It is intended to serve the following interests and functions.

(1) System Buyer - To establish realistic level-of-service criteria, to evaluate supplier proposals, and to assess the impact of design changes during system design and construction.

(2) System Supplier - To assess impact of equipment failure characteristics, to determine compliance with performance specification, and to assess the impact of reliability/maintainability enhancements.

(3) System Operator - To establish performance monitoring information needs, to monitor system performance, to assess the effectiveness of failure management strategies.

The major conclusion drawn from the research[a] are:

(1) The desired parameter to be controlled by service availability considerations is passenger delay. The precise form of expressing levels of control and specific parameters of control vary greatly among applications; however, all are related to delay frequency, duration, and type.

(2) The propensity of a transit system to induce passenger delays is a complex function of several equipment variables, the operating performance induced by these variables, and the interaction of this performance with passenger demands, both link loadings and origin/destination flows.

(3) The relationship between passenger delays (effect) and transit system failures (cause) is a unique property of each specific system. That is, there is no quantitative formula for calculating failure-induced delays that can be applied to all system configurations and operating characteristics.

(4) It follows that no single measure and relationship are sufficient to characterize service availability associated with competing technologies used in different applications.

(5) Knowledge of the passenger-delay transit-system-failure relationship, appropriate to any given technology and application, is crucial to the execution of an effective process of controlling passenger delay performance through system design and operation.

(6) Control of Service Availability can be accomplished via careful selection and control of system design characteristics and operating procedures.

Hence, two generic measures emerge as required to control service availability; the first expressing criteria from a passenger orientation (SAM 1) and the second expressing requirments from an equipment performance orientation (SAM 2). The crucial element in an overall control process is the logical relationship between these. Therefore, a key part of the guidelines in this document is a methodology for relating system equipment performance

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(a) The technical details of the research are contained in Volume II characteristics and passenger delay parameters as appropriate to simple systems and application.

To fully examine the relationship between passenger delays and transit failures, in view of its complex nature, requires simulation techniques. For complicated systems, characterized by general network-type configurations and demand service operations, computer simulation is required. For simpler systems, however, manual "simulation" techniques appear to be suitable. These simple systems include loops, shuttles, and line-haul systems with a fixed route structure and scheduled service operations. It is these latter systems for which this document was prepared.

The remainder of this document is divided into three sections. Section 2.0 discusses the process of controlling service availability during the four AGT life-cycle phases during which control can be exerted. Section 3.0 presents the methodology for relating system failure characteristics and passenger delay potential as required in the service availability control process. Section 4.0 presents a complete example of applying the principles of Sections 2.0 and 3.0.

2. SERVICE AVAILABILITY CONTROL PROCESS

This section presents an overview of the process involved in selecting service availability criteria, controlling system design and construction to assure compliance with the selected criteria, and the determination of the level of service provided by an operational AGT system. Various Government agencies, consultants and suppliers will be involved in the design, construction, testing and operation of an AGT system. To enhance the understanding of the service availability control process explained in the following paragraphs, the terms of "Buyer" and "Supplier" have been selected to simplify the explanation of the overall process. The "Buyer" includes all consultants, planners, designers, and operations and maintenance personnel assisting an agency in the procurement and operation of an AGT system. The "Supplier" includes all consultants and subcontractors assisting the system contractor in the design, construction, and testing of an AGT system.

The life of an AGT system can be separated into the following four distinct time phases:

(1) Planning and Preliminary Engineering Phase
(2) Supplier Selection Phase
(3) Design, Construction, and Testing Phase
(4) Operational Phase.

No definite length of time can be assessed to each phase because of the vast differences involved in each specific AGT application, but there does exist a distinct and identifiable interface between each of the phases. These interfaces will be explained in the discussions of the control process presented below.

Throughout the narrative of this section, the word "methodology" is used to refer to the methodology involved in transforming AGT system equipment failure characteristics to passenger delay parameters during off-normal operation as given in Section 3.0 of this document. The use of this methodology during the four phases of the development and operation of an AGT system is explained in the paragraphs which follow. A summary chart showing the highlights of the control process is presented in Figure 2-1. The enclosed boxes are activities which may involve the use of the methodology.

PLANNING AND PRELIMINARY ENGINEERING PHASE	SUPPLIER SELECTION PHASE	DETAIL DESIGN, CONSTRUCTION, AND TESTING PHASE	OPERATIONS PHASE
Idea for System is Born	Supplier Develops System Design for Proposal	Supplier Performs Detail Design of System	Buyer Collects Operational Data to Use With Methodology
Initial Planning Accomplished	Supplier Completes List of Requested System Parameters	Supplier Builds System	Buyer Uses Methodology to Assess System Changes in Demands and Operation
Performance Measures Selected	Supplier Calculates Expected MTBF's and MTTR's of Proposed System Including Acceptance Equipments	Supplier/Buyer Suggest Changes	Buyer Uses Methodology to Monitor System Service
Selection of Service Availability Measures (Passenger Delay Parameters) is Made	Supplier Uses Methodology to Show Conformance With RFP	Supplier/Buyer Use Methodology to Evaluate Changes	
Assumptions Made of Unknown System Parameters Which Affect Passenger Delays	Supplier Submits Proposal	Supplier Performs and Buyer Witnesses System Acceptance Tests	
Methodology Used to Confirm Reasonableness of Service Availability Measures	Buyer Evaluates Proposals Using Methodology	System Operation Conforms to Acceptance Test Criteria	
Equipments/Subsystems/Systems Chosen for Acceptance Measures	Buyer Selects Supplier for System	System Accepted by Buyer	
List Made of System Parameters to Request of Supplier	Contract Negotiated Which Includes MTBF and MTTR Criteria for Acceptance as Requested in RFP		
RFP Completed and Distributed			

FIGURE 2-1. SERVICE AVAILABILITY CONTROL PROCESS

2.1 Planning and Preliminary Engineering Phase

The Planning and Preliminary Engineering Phase is the initial phase in the development of an AGT system. The idea is "born" and the Buyer begins to plan the system. Considerable time is spent in investigating and determining the various system characteristics desired for the AGT system. System location, expected ridership, and environmental effects are examples of the many considerations which must be addressed during this initial phase of an AGT system's life. Each of these system characteristics must be developed by the Buyer to the point where the system requirements can be combined into the System Performance Specifications. Generally, as the name suggests, the desired system characteristics are specified in terms of system performance such as trip times, origin-destination ridership levels, desired operational capabilities, etc. However, the Performance Specifications also provide the Buyer with the forum to present desired requirements not necessarily related to system performance. For example, if the Buyer wants a certain size or range of vehicle capacity, it is included in the Performance Specifications. If station doors or rubber-tired vehicles are desired, these requirements are included in the Performance Specifications.

As the system planning and design develops, many system characteristics take shape. For instance, general system guideway layout is determined, the location of the stations to be served are determined, and estimates of origin-destination ridership demands are developed.

At the same time, it is necessary that the Buyer select service availability requirements to include in the Performance Specifications. The specific manner in which they are specified may take several forms and the specific values chosen would reflect the Buyer's consideration of desired level of service, system reliability potential, and costs. Traditionally, equipment (subsystem and/or system) reliability values of MTBF and MTTR have been specified, either separately or combined, to form system availability requirements. The methodology presented in Section 3.0 provides a tool for the Buyer to evaluate the impacts of traditional equipment reliability requirements on the person who judges system service, the passengers. Thus, the methodology provides the Buyer with the opportunity to specify service availability in a form which identifies an acceptable level of service (LOS) to the passengers; e.g.,

Probability of incurring a delay on an average trip
Probability of incurring a station delay
Probability of incurring an en route delay
Probability of incurring an en route stoppage
Average delay associated with the previous delays
Average delay encountered on average trip
Cumulative number of delays expected for an average passenger over some period of time
Cumulative delay experienced by an average passenger over some period of time
Exclusive combinations of the above.

The precise form and value of the service availability criterion are Buyer's decisions--based on his goals and insight into passenger expectation and sensitivities.

When the Buyer selects these passenger delay criteria, he chooses a specific degraded level of service which he has determined to be acceptable to the system passengers during those times when the AGT system is experiencing abnormal operation. Normal failure-free operation is by definition free of passenger delays. A "failure", therefore, must be defined to be any system anomaly which causes nonnormal service (delays) to the passengers. "Failures" may involve vehicle stoppages, vehicle slow speeds, shortage of vehicles, station door failures, power system failures, etc.; any system anomaly which causes delays to passengers in vehicles and/or stations must be identified as a "failure".

During the process of establishing the service availability specification, the methodology can be used to judge the reasonableness of the specific values selected. However, to utilize the methodology requires information regarding the specific operating and failure characteristics of the system being analyzed--information which will only be available upon receipt of the proposals during the next phase of the AGT system's life. Therefore, to utilize the methodology to test the reasonableness of the service availability specification requires that the Buyer make educated assumptions for the unknown system parameters, based on his general knowledge of the range of specific system characteristics available or anticipated.

Only after receiving the proposals from the Suppliers can the Buyer assess whether or not a Supplier's proposed system meets the service availability requirements. To do this requires that the Supplier provide, in his proposal, all information necessary to exercise the methodology. This requirement for information must, therefore, be a part of the Performance Specification, together with an explanation of how the information will be utilized to evaluate conformance of the proposed system with the specified service availability measure. This information should include a general operating scenario in which the Supplier describes the normal operating characteristics of his proposed system together with a general discussion of perturbations; i.e., off-normal performance, due to failures. Included would be a discussion of failure management strategies and other special characteristics of his proposed system to enhance service availability. Additionally, the Buyer should request a summary failure mode and delay effect analysis (FMDEA). This analysis provides the "data" required for evaluating the service availability aspects of the proposed system. The FMDEA should list the following for each "aggregate failure mode":

(1) Brief identification of the failure mode
(2) The type of failure. The methodology treats three general types:
    (a) Failure which causes vehicles to stop
    (b) Failures which cause vehicles to proceed at reduced speed
    (c) Failures which require the system to operate with a reduced number of vehicles
(3) The effect of the failure on the operating capability of the system
(4) The effect of the failure on the passenger-trip service capability of the system (e.g., which trips are affected by the failure)
(5) The meantime to restore the system equipment to normal operations
(6) The predicted failure rate.

The term "aggregate failure mode" requires clarification. While the above information could be provided for each detailed failure mode of the system, it is desired for the FMDEA that these be aggregated as near as possible to the system level. Therefore, all failures which exhibit common effects (items 2, 3, and 4 in the above listing) should be combined into aggregate failure modes. Exhibit 8 of Section 4.2 illustrates an example FMDEA.

This information will provide a basis for evaluating service availability specification compliance during the proposal evaluation phase. Determining compliance during the system testing phase, however, is an additional problem. Compliance testing can best be performed if the test criteria are in the form of allowable MTBF's and MTTR's for major systems or subsystems. Hence, the Buyer should request this information to be provided in a Supplier's proposal. These failure statistics should be the basis for the FMDEA. The Buyer may elect to specify the equipment categories for which the failure statistics are to be provided (e.g., vehicles, stations, guideway elements, central control, etc.) or he may permit the Supplier to define his own equipment categories as appropriate to the particular failure characteristcs of the proposed system. In either case, the intent of this information is to provide a basis for compliance testing of the operational systems. This acceptance process will be further explained in the next phase in the life of an AGT system.

The process involved in this Planning and Preliminary Engineering Phase in the life of an AGT system can now be summarized in steps as follows.

(1) Initial planning of the system by the Buyer including overall service decisions of rights-of-way, station locations, system sizing, etc.

(2) Detailed planning by the Buyer to select desired system parameters including origin-destination ridership projections, trip times, frequency of service, vehicle size if desired, station doors, etc. Passenger service availability values are also selected at this time.

(3) Preparation of the Performance Specifications to include in the RFP for the system. In addition, an explanation of the methodology which the Buyer will use to evaluate the passenger service aspects of the proposed system must be included. Each item of system specific information which the Buyer will need to utilize the methodology must be requested in the RFP.

(4) The RFP must include an explanation of the planned procedures for acceptance of the system. It must be clearly stated that certain values of equipment and/or system MTBF's and MTTR's will be monitored for acceptance. These specific MTBF and MTTR values will have been determined by the Supplier in response to the passenger service availability requirements of the Specification.

The Planning and Preliminary Engineering Phase will be complete when the RFP is sent out to prospective Suppliers.

2.2 Supplier Selection Phase

Supplier Selection Phase in the life of an AGT system involves the preparation of proposals by system Suppliers, the evaluation of those proposals by the Buyer, and the selection of a Supplier to build the system. The methodology of evaluating the passenger delays caused by equipment failures is utilized by both Buyer and Supplier during this phase.

During the preparation of the proposal, each Supplier must evaluate his specific equipment and select operational strategies such that the system he proposes will comply with the passenger service availability requirements in the RFP. He will perform trade offs of numbers of vehicles, vehicle size maintenance sidings, location of maintenance areas/personnel, extra guideway to by-pass stalled vehicles, etc., to arrive at his optimum system which complies with the specified criteria. To accomplish this, the methodology identified in the RFP will be used.

In determining the system parameters which meet the specified criteria, the Supplier will develop the FMDEA summary as requested in the RFP. He may, if he desires, include the calculations utilized to arrive at the conclusion that his system will, in fact, meet the passenger service availability requirements of the Specification.

The Supplier will also include in his proposal the equipment/system MTBF's and MTTR's requested in the RFP which will be used as system acceptance criteria in the contract to build the system.

Upon completion, each Supplier will submit his proposal to the Buyer. The Buyer must then evaluate each of the proposals and select a "winner" to build the AGT system.

The primary tool for determining the conformance of the proposals to the passenger service availability requirements is the methodology explained in Section 3.0. Using the methodology for each proposed system may result in a different model being developed, because of each system's specificity. The methodology will provide a common basis of comparison of the passenger delay responses of the proposed systems.

After evaluating the proposals for all aspects of the system, the Buyer selects a winner and a contractual agreement is drawn up. This contractual agreement will not include requirements to prove conformance to the passenger service availability requirements of the Specification. Rather, the equipment and/or system MTBF and MTTR criteria submitted by the Supplier in the proposal will be the criteria used in the contract for system acceptance. This provides for a clear and workable set of acceptance values which can be verified during system testing. The process involved in arriving at these acceptance values assures the Buyer that if the equipment meets the MTBF's and MTTR's, the system will perform as he desires from the standpoint of passenger level of service.

The Supplier Selection Phase in the life of an AGT system ends with the signed contractual agreement between the Buyer and the selected Supplier.

2.3 Detail Design, Construction, and Testing Phase

Following the signing of the contractual agreement to purchase the AGT system, the Detail Design, Construction, and Testing Phase begins.

Service availability considerations are not in the forefront during the early part of this phase in the life of an AGT system. The Supplier is occupied with the detail design and construction of the system. However, as the design and construction of the system progresses, there will undoubtedly be areas discovered where changes to the system will be thought to improve the final product. These changes may be initiated by either the Supplier or the Buyer and their impact on the completed system must be evaluated. Since the

Buyer will be interested in the effect of such changes upon the passengers who will be using the system, the methodology of Section 3.0 can be a useful tool in the evaluation of the suggested changes. If it can be shown that a change in equipment or operational strategy will decrease passenger delays, the Buyer is much more likely to approve such changes and may in fact be willing to pay for them.

During the final period of the Detail Design, Construction, and Testing Phase, the system will undergo acceptance testing to verify that the final product conforms to the contractual agreement. This testing will involve monitoring of the equipment/system failures and comparing them with the contractual MTBF's and MTTR's of major systems/subsystems.

When the system acceptance testing demonstrates that the contractual requirements are met, the system is accepted by the Buyer and the Supplier is relieved of all responsibility other than possible warranties of equipments. This acceptance of the system by the Buyer marks the end of the Detail Design, Construction, and Testing Phase.

2.4 Operations Phase

The Operations Phase in the life of an AGT system extends from the date of acceptance of the system from the supplier until the system is retired. Throughout this lengthy period of time, the Buyer will want to evaluate the level of service being provided to the passengers.

During the initial operational period after accepting the system, the Buyer may want to compare the actual system service with the expected service identified during the planning and design of the system. This can be accomplished by using the methodology outlined in Section 3.0. There may, of course, have been changes in the system from the initial estimates. In particular, the passenger demands and origin-destination flow rates may be different from the design values. It will be necessary, therefore, that the Buyer collect the data for input into the model derived from the methodology. The data required will, of course, be the same type of data needed from the Supplier during the Supplier Selection Phase of the AGT system life. Using actual system failure data, the

Buyer can calculate the passenger delay service availability measures to compare with the early design values.

This measurement of passenger delays will be of interest throughout the life of an AGT system. As ridership changes and as operation/maintenance strategies change, the impact of the changes can be assessed through the use of the methodology. Because of the need for the Buyer's operations personnel to report system service to management, the use of the methodology throughout the Operations Phase appears to be a quite valuable tool.

3. METHODOLOGY FOR RELATING SYSTEM FAILURE CHARACTERISTICS AND PASSENGER DELAY CRITERIA

The key ingredient in the control process discussed in Section 4.0 is a consistent methodology to assess the impact of system failures on passenger delays. To respond to the variety of circumstances of its intended use, this methodology must have the capability of adapting to a variety of situations where delay criteria may vary, the level of specific knowledge regarding the failure characteristics of a system may vary, and the purpose for relating these may vary. It is within this setting that the methodology presented in this section was developed.

In the subsections which follow, the methodology may appear to be characterized by a set of mathematical expressions which can be used in a "cookbook" fashion to establish the passenger delay characteristics of a specific system for a specific application. This conclusion is not entirely correct.

These derived expressions are necessary to mathematically describe service degradation as required to permit quantitative analysis and manipulation of influencing variables. However, the methodology also requires a qualitative understanding of the service interrupting effects of failures to guide the selection and use of the appropriate mathematical expressions (or derivation of additional expressions if necessary). This qualitative understanding is derived through a manual modeling process which enables one to "visualize" normal service characteristics of the transit system being analyzed and "observing" the degradation in service resulting from system failures. It follows, therefore, that the methodology described herein is appropriate only for relatively simple systems where such an understanding can be derived. Typically, such systems include loops, shuttles, and/or line-haul systems (or combinations of these) which have a fixed route structure and a predictable "normal" service pattern. For complex systems, characterized by multiple route network configurations with alternate paths between stations, and random service-on-demand service patterns, the ability to visualize system operations and the validity of the assumptions supporting the mathematical relationships in this methodology are obscure. A general treatment of delay impacts of failures for such complex systems would require computer simulation.

3.1 Methodology Overview

In its simplest form, the methodology developed in this manual involves the rather straightforward process of "observing" the impact of system failures on normal passenger movement through the system. The observation ports are taken to be those points where passenger delays accrue--specifically stations and guideway links. Briefly, the methodology involves postulating failures and computing their impacts on delays at each of the analysis locations in terms of the number of passengers delayed and the duration of the delays experienced. These are then summed in accordance with the expected frequency of occurrence of the failures to arrive at system-level performance values for some selected period of time. This delay "data set" can then be manipulated as necessary to interface directly to the form in which delay criteria were established (SAM 1).

The complexities of the methodology result from the variety of variables which may impact these values.

(1) Failure type - classified by the effect of the failure on the ability of the system to deliver required capacity in the vicinity of the failure. Three types are considered: (a) failures which result in a blockage, (b) failures which result in operations at velocities less than the normal velocity, and (c) failures which result in operations with less than the required number of vehicles.

(2) Failure rate - the expected number of failures in some unit of time.

(3) Failure duration - the time during which the failed state exists.

(4) Failure location - the location of the failure relative to the general system configuration. This is important where failure tolerance is provided.

(5) System failure tolerance - the ability of the system to react to failure situations by bypassing or otherwise disconnecting the failure affected area. This feature determines the extent to which a specific failure disturbs total system performance.

(6) Passenger trip demands - in terms of the quantity of trip requests per unit time.

(7) Trip origin-destination patterns.

(8) System capacity - more appropriately, excess capacity or the ability of the system to handle demand overloads.

(9) Options for introducing additional capacity to recover from a failure.

(10) Time of failure - this is not a primary variable but one where impact is reflected in all those above which are functions of time.

The methodology consists of several steps which sequentially "build" a delay model for any specific situation defined in terms of the above variables. Furthermore, station delays and en-route delays are treated separately; not only because the mechanisms of delay differ, but also because the criteria for these delays may differ in that the buyer may want to "weight" en-route delays different from station delays.

3.2 Procedures for Estimating Delays at Stations

There are two basic mechanisms which induce delays at stations.

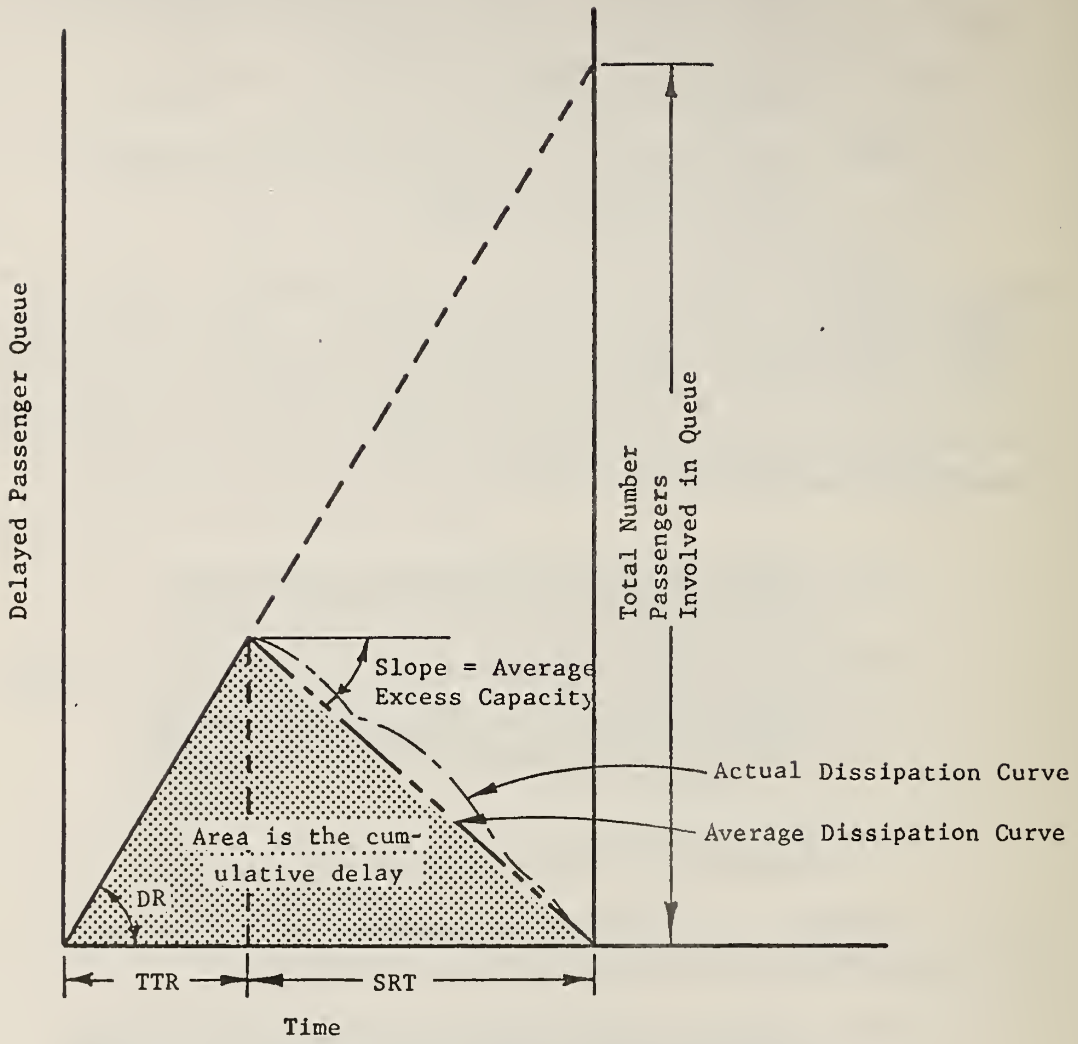
(1) Delays which accrue as a direct result of transportation service being denied at a station due to a failure

(2) Delays which accrue as a result of the passenger queues which result from a denial of service.

Figure 3-1 is a generalized representation of these delays. In this figure, the following time elements are represented:

(1) A "time to restore" (TTR) is indicated which represents the system downtime at that station. The term stands for the time required to make the equipment aspects of the system operate normally, e.g., vehicles following normal speed/distance/headway profiles. This related to "mean time to restore" (MTTR) in most availability discussions.

(2) A "service restore time" (SRT) term is indicated which represents the additional time (beyond TTR) required to reduce station queues and, hence, their effects to normal conditions.



DR = Passenger Service Demand Rate

FIGURE 3-1. GENERALIZED REPRESENTATION OF PASSENGER DELAY PARAMETERS FOR STATION DELAYS

During TTR, passenger demands at the station accumulate at a rate equal to the normal demand rate at that station. After the system equipment elements are restored to normal operation, this delayed passenger queue dissipates in some manner which is determined by the excess capacity of the system available at that station.

Figure 3-1 represents a method which can be used to determine the number of passengers involved in the delay queue as well as the cumulative delay experienced by these passengers. In this figure, the queue dissipation curve is purposely indefinite; it represents the "unknown" quantites associated with passenger delays at stations. Specifically, these quantities are the time to reduce the delayed queue to zero (SRT) and the shape of the delayed queue curve during this dissipation process. Both quantities are influenced by

(1) Demand rate (DR) at the station being analyzed

(2) The excess capacity of the system available after a failure

(3) The competition for this excess capacity from upstream stations, as determined by delayed queues at these stations, the demand rate at these stations, and the O-D patterns of trips generated at these stations.

It would be possible to generate such curves for each station, for each value of TTR expected in a given situation, and for each failure type to derive the overall system station delay profile for a given analysis situation. However, the methodology contained herein does not require this approach. Rather, it utilizes the concept of a "unit failure" which is a hypothetical failure in which the entire system stops for some arbitrarily selected value of TTR. The passenger delay response to this failure is determined. This unit failure analysis essentially defines the relationships among factors 6, 7, 8, 9, and 10 of the list given in Section 3.1 for a "full-stop" failure of some arbitrary duration. Simple scaling procedures are then used to extrapolate this unit failure response to reflect the other factors given in this list. This procedure is illustrated in Figure 3-2.

In the following subsections, procedures are given to determine the unit failure response and scaling relationships for a number of possible

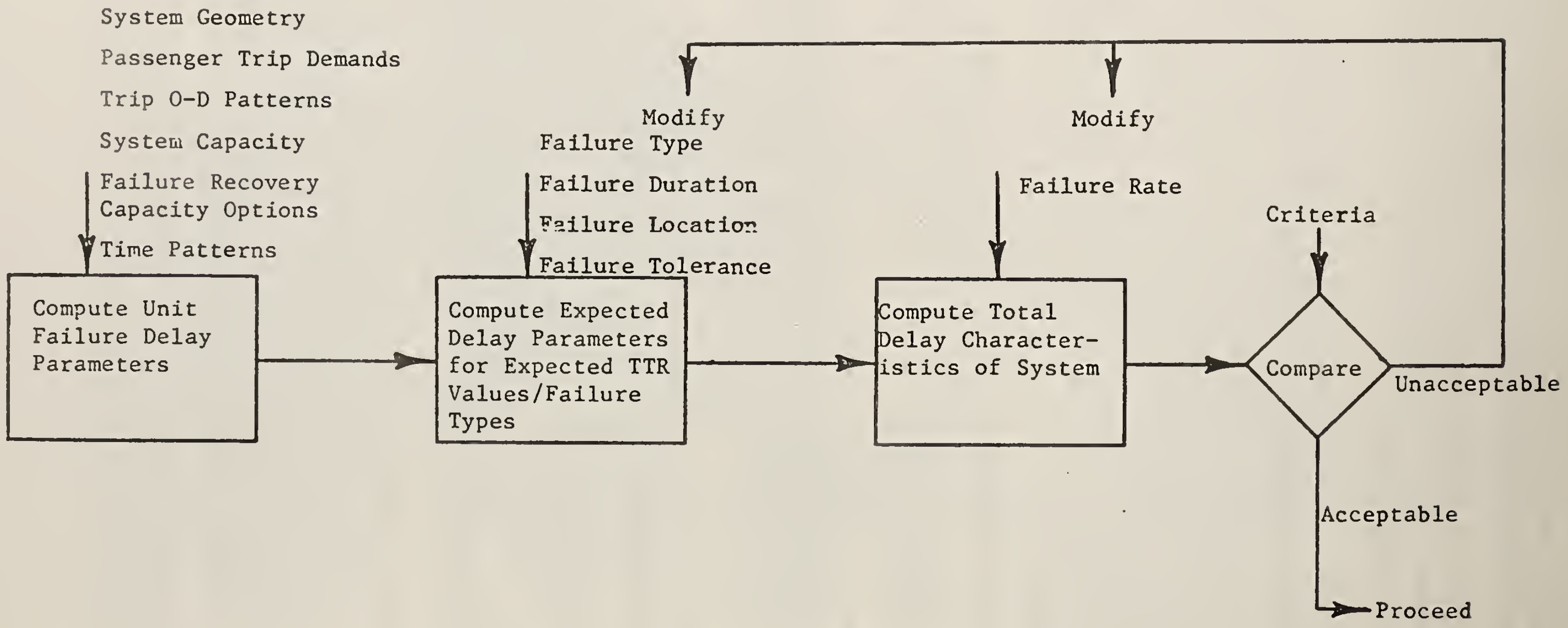


FIGURE 3-2. PROCEDURE FOR DERIVING STATION DELAY PARAMETERS

variations in the factors listed in Section 3.1. In any specific transit system analysis, these factors would be defined and the analyst would select those relationships which are appropriate.

3.2.1 Determination of Unit Failure Response

As indicated above, the delay performance at a specific station can be approximated graphically, the geometry of which defines the delay parameters resulting from a failure of TTR duration. It was also pointed out that the shape and duration of the queue curves were the unknown variables, being complicated functions not only of the delay dynamics of the station being analyzed but also those of other stations in the system. The following procedures enable graphics, such as Figure 3-1, to be quickly generated.

3.2.1.1 Determination of SRT. With reference to Figure 3-1, regardless of the shape of the queue dissipation curve, it follows that SRT is given by

$$SRT = \frac{DR \cdot TTR}{EC_a} \qquad (1)$$

where: SRT = Service restore time (time to dissipate queue to zero, restoring service demands at station to normal levels)

DR = Normal trip demand rate originating at station being analyzed

TTR = Time to restore equipment to operating condition

EC_a = Average excess capacity available for queue dissipation at station being analyzed.

Following a system failure, the average excess capacity available to dissipate queues at any given station is less than the normal excess capacity at that station due to competition from upstream stations. If it is assumed that the normal excess capacity available at a station is shared by through passengers and originating passengers in proportion to their normal volumes, the following relationship results:

$$EC_a \approx \frac{DR}{LF} \cdot EC_n \qquad (2)$$

where: DR = Normal trip demand rate originating at station being analyzed

LR = Normal link flow rate downstream from station being analyzed

EC_n = Normal excess capacity at station.

If the excess capacity for queue dissipation is derived solely from vehicle capacity considerations, Equation (2) becomes

$$EC_a \approx DR \left[\frac{1 - LF}{LF}\right] \qquad (3)$$

where: LF = The load factor of vehicles leaving the station during normal conditions (passengers on board divided by vehicle capacity).

Similarly, Equation (1) becomes

$$SRT \approx \left[\frac{LF}{1 - LF}\right] \cdot TTR \qquad (4)$$

Additionally, if the system has the capability to increase vehicle operating velocity as a method of recovering from a failure, Equation (2) becomes

$$EC_a \approx \frac{DR}{LF} \left[\frac{V_r}{V_n} - LF\right] \qquad (5)$$

where: V_r = Vehicle velocity during the service restoration

V_n = Normal vehicle velocity

and Equation (1) becomes

$$SRT \approx \left[\frac{LF}{\frac{V_r}{V_n} - LF}\right] \cdot TTR \,. \qquad (6)$$

The net effect of increasing vehicle velocity is a decrease in vehicle headways--in terms of time. The same effect can be achieved by decreasing vehicle spacing by inserting more vehicles into the system. With this scheme, Equation (2) becomes

$$EC_a \approx \frac{DR}{LF}\left[\frac{N_r}{N_n} - LF\right] \tag{7}$$

where: N_r = Number of vehicles during recovery time

N_v = Number of vehicles during normal operations

and Equation (1) becomes

$$SRT \approx \left[\frac{LF}{\frac{N_r}{N_n} - LF}\right] \cdot TTR\ . \tag{8}$$

In many systems, these latter two options may not exist, either by design (velocity limits) or practical constraints (unavailability of extra vehicles or the inability to quickly dispatch and insert extra vehicles as required to recover from a failure). Hence, from a service recovery standpoint in most systems, vehicle size will be the most influential parameter.

The above relationships serve to define SRT which, in turn, define a point in time following a failure when the delayed passenger queue is reduced to zero and the effect of the failures are no longer apparent to a new passenger entering the station being analyzed. Knowing SRT allows the number of passengers involved in the delayed queue to be estimated as will be discussed in a subsequent section. To determine the delay imposed on these passengers, however, the shape of the dissipation curve must be known.

3.2.1.2 Estimation of Queue Dissipation Curve Shape. The estimation of SRT utilizes an average value for excess capacity over the duration of the queue dissipation process. At any point in time during this process, however, the actual excess capacity at the station being analyzed can vary considerably from this average value. Like the average excess capacity, these intermediate excess capacity values are complex functions of queue dissipation dynamics interacting among stations. However, knowing SRT, at all stations from some value of TTR, reasonable approximations for the delay curves can be generated.

This process can best be illustrated through the use of an example. This example will also serve to illustrate the concepts discussed in the previous section. Figure 3-3 illustrates the system used in this example. This system incorporates features such that any failure effects the entire system. As illustrated, four vehicles are used and indexed between stations.

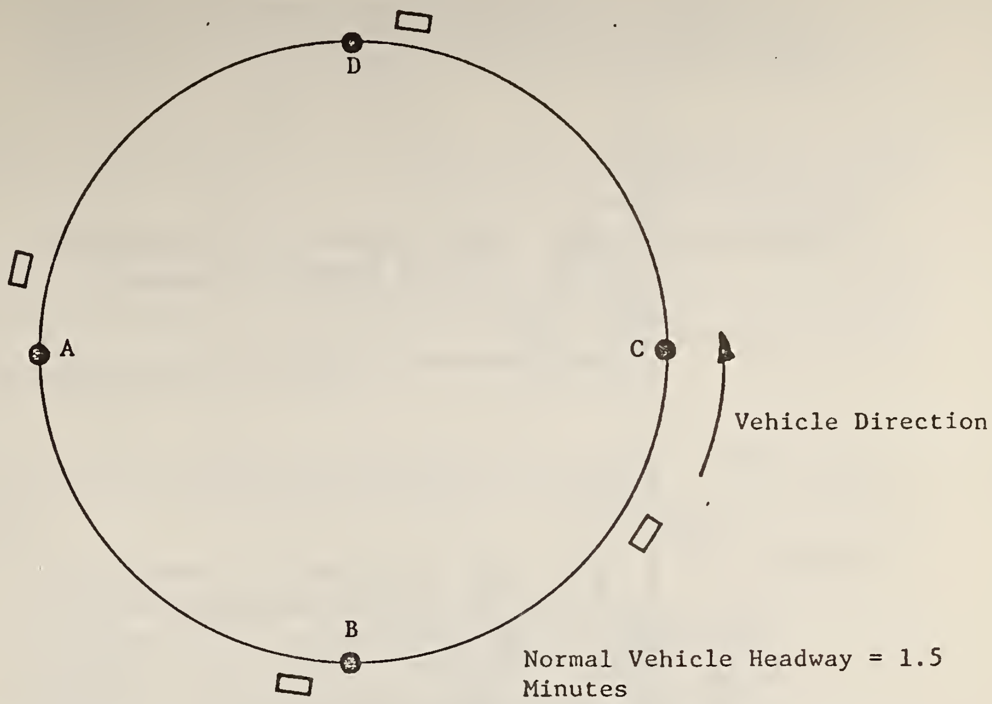
The link loading data in Figure 3-3 shows a maximum vehicle loading under normal conditions to be 25 passengers. This occurs on Links C-D and D-A. To provide excess capacity, a vehicle maximum loading value of 30 passengers is used.

Figure 3-4 illustrates the delay envelopes for each station in this hypothetical system. Station "C" is highlighted for this discussion. As noted, the delay envelope is generated in three steps.

(1) The initial rise of the delay envelope has a slope equal to the demand rate at that station and exists for a duration of TTR--in this case, two normal vehicle headway intervals.

(2) SRT is computed using appropriate equations from Section 3.2.1.1. In this case, excess capacity is derived solely from vehicle size. Therefore, Equation (4) is used, which, with the data provided in Figure 3-3 yields the following value for SRT for Station C of 5 TTR. This point is located on the delay envelope axis.

(3) The points defined by (1) and (2) are connected to complete the diagram. This connection process itself involves two steps. As noted previously, demands at each station compete for the normal excess capacity of a system. This competition is most fierce between adjacent stations. For example, with the four stations of the example, the queue dissipation capability at Station C is most influenced by the queue at Station B. It is influenced to a lesser extent by the queue at Station A because Station B, an intermediate station, acts as a buffer--some passengers from A exit at Station B. Therefore, as a first approximation, it is assumed that once the queue at Station B is dissipated, it is no longer competing for the system excess capacity. Therefore, after the queue at B is dissipated, the average excess capacity at Station C is the normal excess capacity (EC_n) which would be available under normal situations. (From Figure 3-3, EC_n at Station C equals 5 passengers per normal vehicle headway interval.) Hence, at Station C, the last part of the delay curve can be approximated. By connecting these segments, a reasonable approximation



Origin-Destination Matrix - Passengers Per Normal Vehicle Headway Interval

From	To	
A	B	4
A	C	4
A	D	2
B	C	2
B	D	2
B	A	8
C	D	1
C	A	10
C	B	2
D	A	2
D	B	2
D	C	1
	Link Loads	
A	B	13
B	C	19
C	D	25
D	A	25

FIGURE 3-3. EXAMPLE TRANSIT SYSTEM

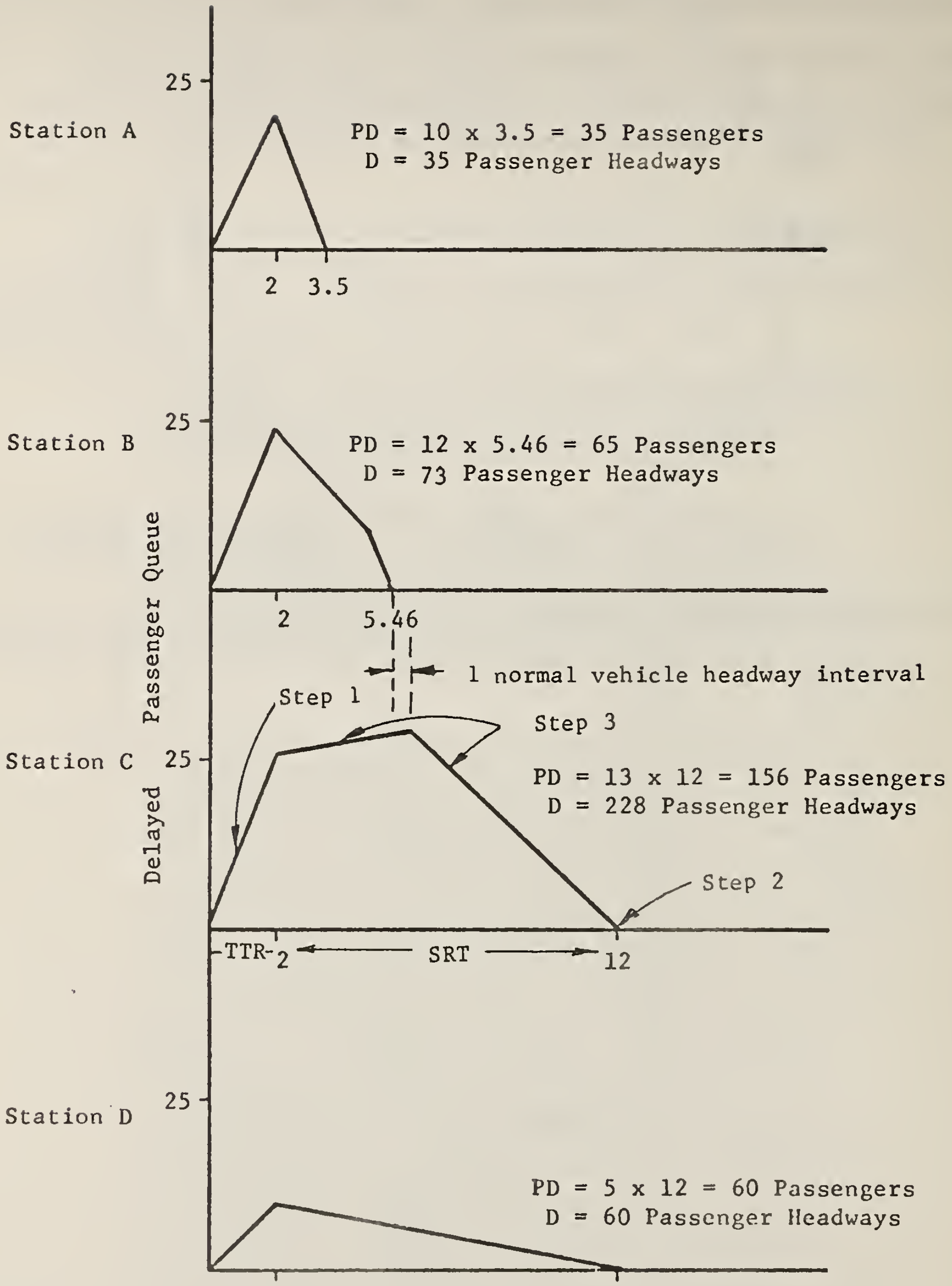


FIGURE 3-4. DELAY ENVELOPES FOR FULL-STOP FAILURE

> to the excess queue curve is developed. Similarly, Station B performance can be developed. Stations A and D exhibit a characteristic triangular shape because the SRT values at these stations are less than those at the immediate upstream stations.

Having these shapes, one can compute the total passenger delay (D) resulting from the postulated failure, as well as the number of passengers delayed (PD). Therefore, all of the delay parameters of concern which result from a postulated failure can be simply computed using geometry, arithmetic, and some judicious thought and visualization about what is likely to happen and after a full-stop system failure.

3.2.1.3 Unit Failure Delay Estimation Procedure. The following steps are required to estimate the unit failure response of a given transit system situation:

(1) Arbitrarily select a time period for a hypothetical full-stop failure to be imposed on the system being analyzed. This value is denoted as TTR*[a]. Certain advantages in computation are realized if the units of time are taken to be "average normal vehicle headway intervals".

(2) Using procedures defined in Section 3.2.1.1, compute the SRT values for each station using the formula appropriate to the system being analyzed.

(3) Using procedures defined in Section 3.2.1.2, generate graphics for delay parameters at each station.

(4) From these graphics, compute the number of passengers delayed (PD_j^*) and the cumulative delay (D_j^*) experienced by these passengers at each station. By summing those values derived from each station, total system delay parameters are derived

PD* = Total number of passengers delayed per unit failure

D* = Total cumulative delay of these passengers per unit failure.

These values are the unit failure response parameters desired.

(a) Throughout this document, the asterisk is reserved to denote "unit failure" parameters.

Determining unit response by this method assumes certain system parameters to be constant, specifically the passenger demand rate (DR), the capacity available to dissipate delayed queues, and the O-D patterns of trips (as these influence load factors). During any specific failure, assuming TTR to be small, these assumptions are reasonable. However, any or all of these parameters may vary over the day. Hence, the unit failure response may vary over time. Therefore, an average response should be determined by repeating the above procedure as necessary for selected time intervals with the results being weighted by the duration of each interval to determine an average unit failure response. Alternatively, the Buyer may arbitrarily select a constant level (such as 0.8 peak value) for design purposes.

Comprehending all variations in these parameters which may exist is a near impossible feat. Therefore, patterns must be selected which represent the typical patterns expected. Figure 3-5 illustrates this thinking for a demand pattern as it may exist, and the approximating patterns appropriate for using this methodology. Emphasis should be placed on close matching of peak demands as these influence delay performance to a greater extent than off-peak values. With such a pattern, the above procedures for determining unit failure response would be exercise through time, with the results time-averaged to obtain an average unit failure response.

3.2.2 Determination of Passenger Delay Parameters for Full System Stoppage Failures

If a transit system exhibits failures of a full-stop type, the following relationship can be used to determine the number of passengers delayed (PD) during an average failure:

$$PD = PD^* \frac{\overline{TTR}}{TTR^*} \tag{9}$$

where: PD = Total number of passengers delayed per average failure

PD^* = Total number of passengers delayed per unit failure

$\overline{TTR}$ = Mean time to restore for full-stop failures

TTR^* = Unit failure downtime.

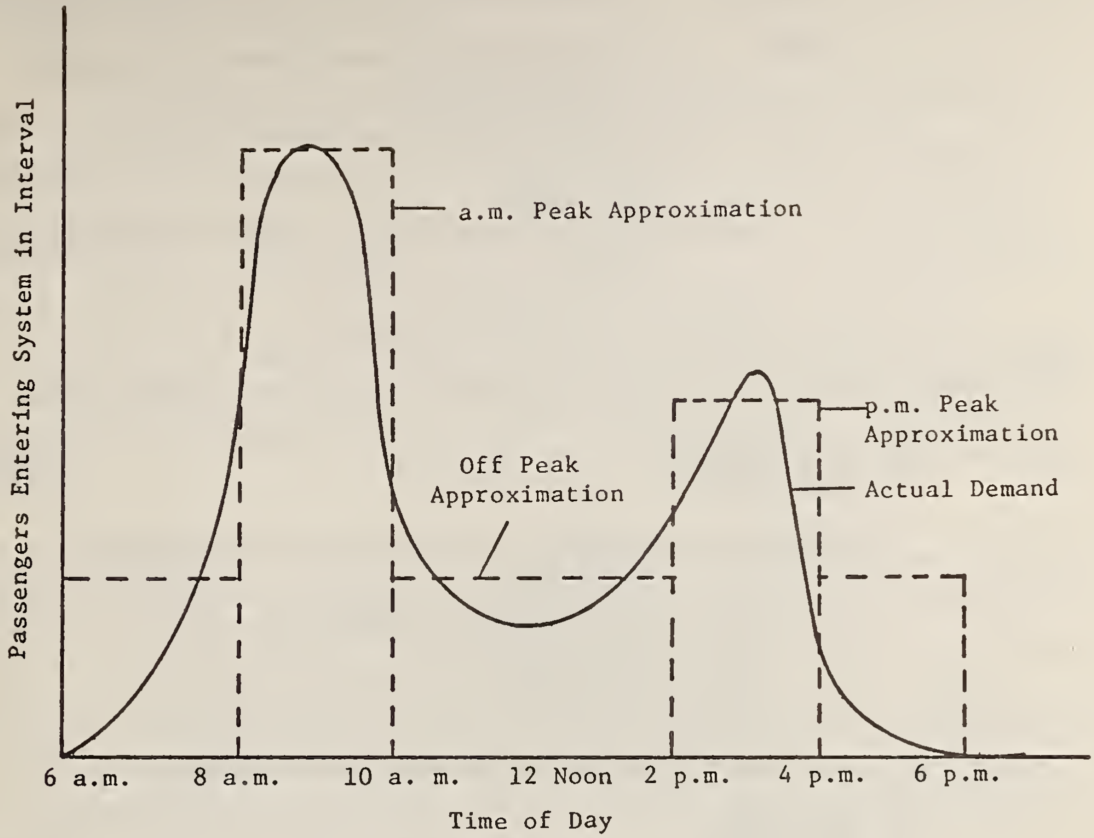


FIGURE 3-5. ILLUSTRATION OF APPROXIMATING VARYING DEMAND PATTERNS TO ESTABLISH AVERAGE DELAY RESPONSE CHARACTERISTICS

The relationship for estimating the cumulative delay (D) experienced by delayed passengers during an average failure is

$$D = D^* \frac{\widetilde{TTR}^2}{TTR^{*2}} \qquad (10)^{(a)}$$

where: D = Cumulative delay experienced by passengers per average failure

D^* = Cumulative delay per unit failure

$\widetilde{TTR} = \sqrt{\frac{\sum_i \lambda_i \overline{TTR}_i^2}{\sum_i \lambda_i}}$, RMS value of $\overline{TTR}_i$ for failure mix

TTR^* = Unit failure downtime.

The probability of delay can be estimated by the following relationship:

$$Pr_d = \frac{PD^*}{DR} \frac{\overline{TTR}\,\lambda}{TTR^*} \qquad (11)^{(b)}$$

where Pr_d = Probability of being delayed at station on an average trip

DR = Total system trip demand rate

λ = Failure rate.

(Other variables defined as before.)

Expected delay can be estimated by the following relationship:

$$ED = \frac{D^*}{DR} \frac{\widetilde{TTR}^2 \lambda}{TTR^{*2}} \qquad (12)$$

where ED = Average station delay expected on average trip.

(Other variables defined as before.)

Care should be exercised in using these relationships to ensure consistency of units. A new term has been introduced, $\widetilde{TTR}$, in the delay scaling procedures. Because delay (the <u>area</u> under the delayed queue curve

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(a) The eauations in this section are all relevant only to full system stoppage failures (the subsection title). Hence, all parameters (excluding unit failure parameters) carry an implicit subscript denoting this relevance. In this document, these subscripts are not included to enhance clarity. This philosophy is continued in all subsequent subsections.

(b) In this formulation, the assumption is made that $\lambda \overline{TTR} << 1$. This is reasonable based on sparse data from existing systems which place values for both of these parameters within an 0.1 magnitude. If this assumption is thought to be too liberal, λ may be replaced with $\lambda/(1 + \lambda\,\overline{TTR})$. This assumption is used generally throughout this document.

of Figure 5-1) is proportional to TTR^2, a quadratic mean (or RMS value) is required to scale unit failure response (D*) properly.

3.2.3 Determination of Passenger Delay Parameters for Full System Stoppage Failures When Headway Closure is Permitted

In situations where one vehicle stops and others are permitted to close in behind (utilizing the "cushion" referred to in many analyses), a downstream vehicle failure may not affect the delay experienced in boarding a system if the failed vehicle becomes operational before safe headway constraints are met. This assumes that there is an unlimited source of vehicles. In most systems, there are a very limited number of vehicles available. Furthermore, if the vehicles "bunch", as they would if the cushion is utilized for closed systems, a passenger at a station would see several vehicles at closer-than-normal headways, then a gap would appear--inducing delays at that station.

Essentially, the appearance of this gap represents another "failure" insofar as service to a station is concerned. It is important to get the system back on normal speed/headway relationships to minimize this recurring failure. If the failure management strategy is to create normal headways immediately following the failure by holding trailing vehicles as necessary, the delay curves at stations are nearly identical to those resulting from a full-stop failure except that they do not occur at all stations at the same time. Rather, they are displaced, in time, from one another.

Headway compression can become a beneficial mode of failure recovery if the lead vehicles in the bunch have an increased speed capability, permitting normal headways to be established without slowing down trailing vehicles. Also, if the option exists for inserting spare vehicles into the system to fill the gap, headway closure would be useful. However, in most systems, neither of these approaches is likely to be available. Therefore, the conclusion to be drawn is that, in terms of delay effects, headway compression capability does not alter the basic delay parameters defined by a full-stop failure; it simply delays the effects and keeps some vehicle movement which helps psychologically.

3.2.4 Determination of Passenger Delay Parameters for Full System Slow Down Failures

If a transit system exhibits a failure type which reduces normal vehicle velocity for some period of time, passengers may experience delay from two sources: (1) delays due to reduced frequency of service and (2) delays due to reduced capacity, if this reduction is sufficient to force queues at stations. Of these two sources, the latter is considered most important to the overall impact of the failure and, hence, in the delay inducing mechanism discussed here.

Because the available capacity varies among stations, only part of the stations may experience a queue buildup. Hence, the delay effects must be evaluated on a station-by-station basis. The general expression defining this process if

$$D_j = \frac{\overline{TTR}_{ss}}{TTR^*} D_j^* \left(\frac{LF_j - V_f/V_n}{LF_j} \right) \tag{13}$$

where: D_j = Cumulative delay incurred at station j due to slow-speed failure

$\overline{TTR}_{ss}$ = Duration of slow-speed failure

TTR^* = Duration of unit failure

D_j^* = Cumulative delay incurred by passenger at station j due to unit failure

LF_j = Normal load factor of link leaving station j

V_f = Vehicle velocity during failure

V_n = Normal vehicle velocity.

Equation (13) is constrained as follows:

If $V_f/V_n \geqq LF_j$, $D_j = 0$.

It follows, therefore, that the number of passengers delayed is accumulated only at those stations where delay is accumulated. the relationship governing the number of passengers delayed is:

$$PD_j = \frac{\overline{TTR}_{ss}}{TTR^*} \left[1 - \frac{V_f}{V_n} \right] PD_j^* \tag{14}$$

where: PD_j = Number of passengers delayed at station j due to queue buildup at stations under a slow-speed failure

PD_j^* = Number of passengers delayed at station j due to unit failure.

(Other variables defined as before.)

In this equation, j takes only values permitted by the constraint imposed on Equation (13).

The relationships governing probability of delay and expected delay are as follows:

$$Pr_d = \frac{\sum PD_j}{DR} \lambda_{ss} \tag{15}$$

where: Pr_d = Probability of incurring a delay on a random trip due to a slow-speed failure

λ_{ss} = Failure rate for slow-speed failure.

(Other variables defined as before.)

The relationship for estimating expected delay is

$$ED = \frac{\sum D_j}{DR} \lambda_{ss} \tag{16}$$

where: ED = Average station delay per average trip due to slow-speed failure.

(Other variables defined as before.)

3.2.5 Determination of Passenger Delay Parameters for Full System Vehicle-Out-of-Service (VOS) Failures

VOS failures behave much like slow-speed failures. There is a certain amount of delay associated with the gap in normal service created by the missing vehicle (s). However, as with the slow-speed failure, the main concern is the loss of capacity and the ensuing queue buildup which may exist. The equations for the delay parameters under this type of failure parallel those for slow-speed failures. The relationship for estimating the cumulative delay at a station is

$$D_j = \frac{\overline{TTR}_{vos}}{TTR^*} \quad D_j^* \left(\frac{LF_j - N_f/N_n}{LF_j} \right) \tag{17}$$

where: D_j = Cumulative delay at station j due to vehicle-out-of-service failure

$\overline{TTR}_{vos}$ = Duration of VOS failure

N_f = Number of vehicles operating during failure

N_n = Number of vehicles normally operating.

(Other variables defined as before.)

The number of passengers delayed may be estimated by the following relationship:

$$PD_j = \frac{\overline{TTR}_{vos}}{TTR^*} \left[1 - \frac{N_f}{N_n} \right] PD_j^* \tag{18}$$

where: PD_j = Number of passengers incurring delays at station j due to VOS failure.

(Other variables defined as before.)

Equations (17) and (18) are constrained as follows:

If $N_f/N_n \geqq LF_j$, then $D_j = 0$ and $PD_j = 0$.

The probability of delay can be estimated by the following relationship:

$$Pr_d = \frac{\sum PD_j}{DR} \lambda_{vos} \tag{19}$$

where: Pr_d = Probability of incurring a delay on an average trip due to VOS failure

λ_{vos} = Failure rate for VOS failure.

(Other variables defined as before.)

The following relationship can be used to estimate expected delay:

$$ED = \frac{\sum D_j}{DR} \lambda_{vos} \tag{20}$$

where: ED = Average station delay per average trip due to VOS failures.

(Other variables defined as before.)

3.2.6 Determination of Passenger Delay Parameters for a Stoppage Failure Affecting Part of the System

The previous types of failures all apply uniformly to complete systems, that is, the failure affects the entire system. Such would be the case with simple circulation systems with on-line stations, no passing capability, no turn-around capability, and no reverse-running capability. For these types of systems, a failure cannot be isolated. For systems where a failure can be "disconnected", allowing the remainder of the system to operate, different failure effects accrue. Only passengers which require use of the failed portion will be delayed. Station queues will develop involving all trips which are affected by the partial system failure. After the failure is removed, these queues will dissipate according to the average excess capacity available at those stations. If the excess capacity is very large relative to the demands, such that these delay queues will dissipate immediately, a relationship exists to the delay parameters computed for a full-stop failure of equal duration. In this situation, the delays incurred at any station are related to those which would result from a full-stop failure by the following relationship:

$$PD_{pf} = PD_{fs} \cdot \frac{T_a}{T_t} \tag{21}$$

where PD_{pf} = Number of passengers delayed at a station due to a partial system failure of TTR duration

PD_{fs} = Number of passengers delayed at that station due to a full-stop failure of equal TTR

T_a = Passenger trips originating at station during the failure which require the use of the failed portion of the system

T_t = Passenger total trips generated at that station during the failure.

If the excess capacity is not large, interaction among station queues again complicates the service restoration process, resulting in deviations from the above relationship. (Equation (21) may estimate either high or low. Fortunately, when all possible partial failures are analyzed for any system, the "over estimates" tend to balance the "under estimates". Therefore, Equation (21) can be considered to represent a reasonable approximating relationship. By generalizing this relationship to the full system and using the unit failure as the full-stop failure, estimates of delay parameters based on unit failure response is accomplished. The expression for number of passengers delayed is

$$PD_k = \frac{PD^*}{TTR^*} \overline{TTR}_k \frac{T_k}{T_t} \qquad (22)$$

where: PD_k = Number of passengers delayed due to a failure which closes the kth portion of the system

PD^* = Number of passengers delayed per unit failure

TTR^* = Duration of unit failure

$\overline{TTR}_k$ = Mean-time-to-restore failure which denies use of the k portion of system

T_k = The number of trips (originating anywhere in the system) which require the use of the kth portion of the system during some time interval

T_t = The total number of trips generated during this time interval.

The cumulative delay experienced by the passenger can be estimated by the following relationship:

$$D_k = \frac{D^*}{TTR^{*2}} \widetilde{TTR}_k^2 \frac{T_k}{T_t} \qquad (23)$$

where: D_k = Cumulative delay of passengers experiencing station delays due to failures of kth portion of the system

D^* = Cumulative delay experienced by passengers due to unit failure

$\widetilde{TTR}_k$ = RMS value of TTRs for failures affecting kth part of the system

(Other variables defined as before.)

By summing these relationships over k, general delay statistics can be derived. The expression for estimating probability of delay is

$$Pr_d = \frac{\sum (PD_k \lambda_k)}{DR} \qquad (24)$$

where: Pr_d = Probability of delay on average trip due to partial system failure

λ_k = Failure rate for failures affecting kth part of the system

(Other variables defined as before.)

Expected delay can be estimated by the following relationship:

$$ED = \frac{\sum D_k \lambda_k}{DR} \qquad (25)$$

where: ED = Average delay expected for an average trip due to partial system failures

λ_k = Failure rate for failures affecting kth part of the system.

(Other variables defined as before.)

3.2.7 Determination of Passenger Delay Parameters for Delays Exceeding Some Allowable Threshold

In certain situations, delay criteria may be established in a form of a probability of being delayed greater than some allowable value, say Δ.

Specifications like this can be readily handled using the procedures outlined for the previous examples if one is willing to accept an approximation which states that, on the average, if a failure detains a group of passengers for a time period of $\overline{TTR}$, all passengers are delayed for exactly $\overline{TTR}$. This, of course, does no accounting for distribution about the mean value. If, for example, a value of Δ is one minute, failure with a $\overline{TTR}$ of slightly less than one minute would not delay any passengers from the standpoint of the $Pr_{d,\Delta}$ calculation. Failures with a $\overline{TTR}$ of slightly greater than one minute would result in all passengers delayed being counted in the $Pr_{d,\Delta}$ calculation. Neither of these is correct, but over a period of time, these effects would tend to average out. Furthermore, if $\overline{TTR}$ is large compared to Δ, this issue is diminished.

Under this assumption, the same equations and procedures developed in the previous subsection for computing station delays are applicable for $Pr_{d,\Delta}$ calculations with a redefinition of $\overline{TTR}$. The principle used to establish the redefinition of $\overline{TTR}$ is introduced in Figure 3-6. This figure is the general delay envelope at a station due to a unit failure of TTR* duration. As illustrated, the number of passengers delayed greater than some time, Δ, can be graphically determined.

By inspection, the following relationship is derived:

PD^*_{Δ} = Passengers delayed greater than Δ time due to unit failure of TTR*

PD* = Passengers delayed greater than 0 time due to unit failure of TTR*

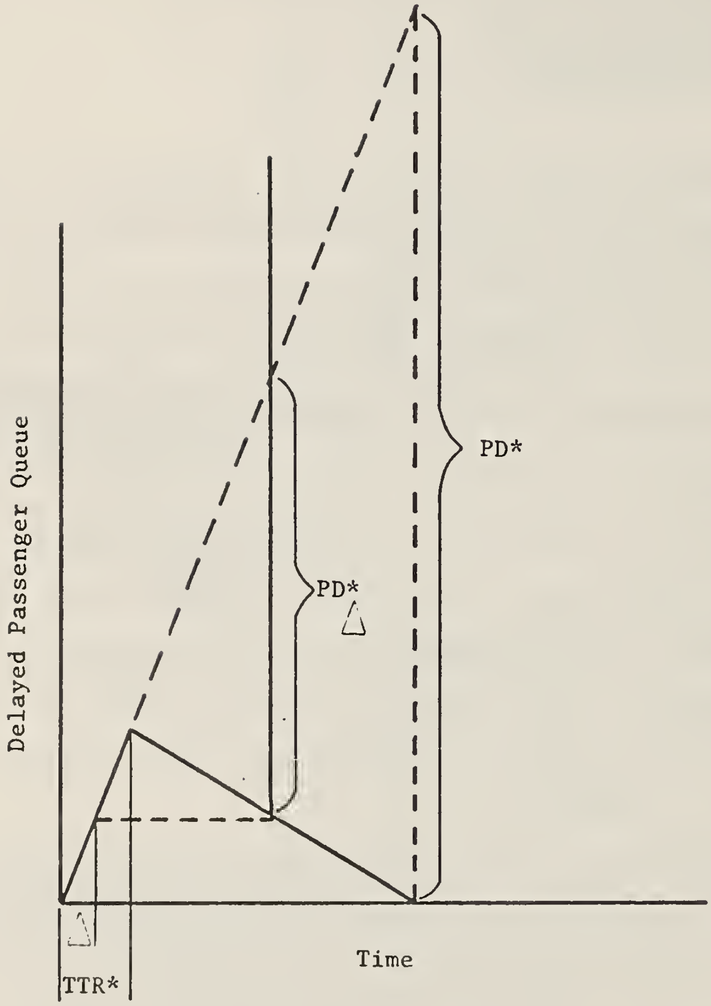


FIGURE 3-6. GENERAL DELAY ENVELOPE TO ILLUSTRATE DELAY INTERVALS

$$PD^* = PD^* \frac{TTR^* - \Delta}{TTR^*} .$$

This relationship is generally applicable; it does not apply solely to a unit failure. In general,

$$PD_{\Delta} = PD \frac{TTR^* - \Delta}{\overline{TTR}}$$

where: PD_{Δ} = Number of passengers delayed greater than Δ due to an arbitrary failure of $\overline{TTR}$ duration

PD = Total number of passengers delayed, for any time duration, due to arbitrary failure of $\overline{TTR}$ duration.

Therefore, the number of passengers delayed greater than Δ can be derived from unit failure responses as follows:

$$PD = PD^* \frac{\overline{TTR} - \Delta}{TTR^*} \qquad (26)$$

By generalizing this relationship, previous relationships for the calculations of Pr_d at stations are applicable if $\overline{TTR}$ is replaced with $(\overline{TTR} - \Delta)$.

3.2.8 Determination of Passenger Delay Parameters for Combinations of Failure Types

If it is assumed that all failures are independent and that a single passenger does not experience more than one failure on a given trip, combination of failure types can be addressed. The procedure involves the determination of delay parameters for each failure type using the previous procedures. These parameters can then be added directly to determine the total system-induced delay parameters.

3.3 Procedures for Estimating Delays Incurred En Route

Obtaining estimates for en route delays is considerably more straightforward than it is for station delays because the complex intra- and inter-station queue dynamics are not present. Hence, an "RT" does not exist for en route delays. Briefly, the procedures for estimating en route delays involve manually simulating failures and "counting" the number of passengers delayed en route for each failure type expected in a given system situation and summing these values in accordance with the expected frequency of each failure type. In the subsections which follow, procedures and mathematical relationships are given for each of the generic failure types used in Section 3.2.

Because of the differences in passenger perception between being slowed en route and being stopped between stations, and because many planners may want to control these effects independently and weight them differently, the subsections which follow treat each of these effects independently.

3.3.1 Determination of Passenger Delay Parameters for Full System Stoppage Failures

3.3.1.1 General Delay Parameters. If a system exhibits failures of the full system stoppage type, each failure will impact all passengers en route on the entire system at the time of the failure. Hence, for each failure, the number of passengers delayed en route

$$PD = N_d C_v \overline{LF} \tag{27}$$

where: PD = Average number of passengers delayed en route for a full stoppage failure

N_d = Average number of vehicles deployed between stations

C_v = Vehicle capacity

$\overline{LF}$ = Average load factor for all vehicles operating.

Cumulative delay can be estimated by the following relationship:

$$\overline{D} = \overline{TTR} \tag{28}$$

where: $\overline{D}$ = Average delay per delayed passenger due to full stoppage failure

$\overline{TTR}$ = Mean time to restore equipment to normal operating levels.

The probability of delay can be estimated by the following relationship:

$$Pr_d = \frac{N_d C_v \overline{LF} \lambda}{DR} \qquad (29)$$

where: Pr_d = Probability of being delayed en route average trip

λ = Failure rate for full system stoppage failure

(Other variables defined as before.)

Expected delay can be estimated by the following relationship:

$$ED = \frac{N_d C_v \overline{LF} \lambda \overline{TTR}}{DR} \qquad (30)$$

where: ED = Average delay expected on average trip due to full system stoppage failures

(Other variables defined as before.)

3.3.1.2 En Route Stoppages. Because of the nature of the failure type, all en route delays will involve vehicle stoppages. Hence, the previous general delay parameters are also stoppage parameters.

3.3.2 Determination of Passenger Delay Parameters for Stoppage Failures Where Headway Closure is Possible

3.3.2.1 General Delay Parameters. The argument given in Section 3.2.4 regarding the effect of cushion utilization also applied for en route delays. Cushion utilization may permit certain passengers to reach their destination without being delayed. However, other passengers which board the system during the failure may experience delays. Further, passengers which board the system after the failure has been removed may experience delays during the process of reestablishing normal vehicle spacing. Therefore, as an approximation, it may be assumed that, in terms of general en route delay potential, the parameters defined in Section 3.3.1.1 also apply to this failure type.

3.3.2.2 Stoppage Parameters. The above argument does not apply to en route stoppage potential. Here, cushion utilization can be effective because the slow-down delays associated with the vehicle spacing process are not counted. To estimate stoppage parameters with cushion utilization, the following relationships apply. These relationships use two new terms.

(1) N_n = Total number of vehicles in the system. This constrains the number of vehicles which can be delayed.

(2) CH - Cushion or closure permitted between vehicles. Generally, this would be the difference between the normal vehicle headway interval and the minimum headway interval determined by safety considerations or operating rules.

In situations where vehicles are permitted to move until constrained by limits of the cushion headway,

$$N = \frac{\overline{TTR}}{CH} \tag{31}$$

where: N = Number of vehicles stopped as a result of the stoppage failure

TTR = Duration of the failure.

[In Equation (31), N assumes integer values obtained by rounding the fraction to the next higher integer.]

Equation (31) is applicable under the following condition:

$\overline{TTR} \leq N_n CH$.

When $\overline{TTR} > N\ CH$,

$$N = N_n \tag{32}$$

The average delay per delayed vehicle is similarly a two-part formulation,

when $\overline{TTR} \leq N\ CH$,

$$D_v = \frac{\overline{TTR}}{2} \tag{33}$$

where: D_v = Average delay per delayed vehicle.
(Other variables defined as before.)

When $\overline{TTR} > N\ CH$,

$$D_v = 3/2\ \overline{TTR} - N_n CH. \tag{34}$$

Passenger delay parameters can be derived from these relationships as follows:

When $TTR \leq N_n CH$, the following relationships can be used to estimate the probability of delay and expected delay.

$$Pr_d = \frac{C_v \overline{LF}}{DR\ CH} \overline{TTR} \lambda \tag{35}$$

where: Pr_d = Probability of incurring a stoppage en route on an average trip

C_v = Vehicle capacity

$\overline{LF}$ = Average load factor of all vehicles

DR = Passenger demand rate

$\overline{TTR}$ = Average duration of failure

λ = Frequency of occurrence of failure.

$$ED = \frac{C_v \overline{LF}}{DR\ CH} \left(\frac{\overline{TTR}^2 \lambda}{2} \right) \tag{36}$$

where: ED = Average duration of en route stoppage expected on an average trip.

(Other variables defined as before.)

When TTR > N_nCH, the following relationships are applicable:

$$Pr_d = \frac{N_n C_v \overline{LF}}{DR} \lambda \tag{37}$$

where: Pr_d = Probability of incurring a stoppage en route on an average trip,

and $$ED = \frac{N_n C_v \overline{LF} \lambda}{DR} (3/2\ TTR - N_n CH) \tag{38}$$

where: ED = Average duration of en route stoppage expected on an average trip.

Many operating strategies may be used to limit the number of vehicles stopped en route (e.g., slowing down trailing vehicles or holding at upstream stations). In these situations, a link-by-link assessment is required to determine the number of vehicles actually involves in a stoppage incident. From this information, passenger delay parameters can be derived.

3.3.3 Determination of Passenger Delay Parameters for Full System Slow-Speed Failures

3.3.3.1 General Delay Parameters. In general, during a failure which restricts vehicle velocity to some level below normal velocity, all passengers boarding vehicles will experience an en route delay. Accordingly, the number of passengers delayed can be estimated by the following relationship:

$$PD = DR\,\overline{TTR}_{ss} \qquad (39)$$

where: PD = Number of passengers delayed en route due to slow-speed failure

DR = Average passenger demand rate (This should actually be passenger boarding rate, which may be less than demand rate. However, using DR is reasonable approximation and errs on the conservative side.)

$\overline{TTR}_{ss}$ = Average duration of the slow-speed failure.

The cumulative delay may be estimated by the following relationship:

$$\overline{D} = TT\left(\frac{V_n}{V_f} - 1\right) \qquad (40)$$

where: $\overline{D}$ = Average delay per delayed passenger due to slow-speed failure

TT = Trip time for average trip

V_n = Normal vehicle velocity

V_f = Vehicle velocity during failure.

The following relationships can be used to estimate the probability of delay and expected delay:

$$Pr_d = \overline{TTR}_{ss}\,\lambda_{ss} \qquad (41)$$

where: Pr_d = Probability of being delayed on average trip due to slow-speed failure

λ_{ss} = Failure rate of slow-speed failures.

$$ED = \overline{TTR}\lambda_{ss}TT\left(\frac{V_n}{V_f} - 1\right) \qquad (42)$$

where: ED = Average delay expected on average trip due to slow-speed failure.

(Other variables defined as before.)

Equation (41) estimates the probability of delay en route due to a slow-speed failure. As discussed in Section 3.2.4, some of the passengers delayed en route will have already experienced a delay at a station. When adding delay parameters to obtain total values, care must be taken to avoid double counting if this is considered to be problematical. Alternatively, one may purposely desire to treat these independently.

3.3.3.2 Stoppage Parameters. Because of the nature of a slow-speed failure, no en route stoppages are encountered.

3.3.4 Determination of Passenger Delay Parameters for Full System Vehicle-Out-of-Service (VOS) Failures

This type of failure does not impact en route delays to any passengers except those aboard the failed vehicle. Hence, on a per failure basis, the number of passengers delayed is equal to the average number of passengers aboard an average vehicle. The duration of the delay incurred must be estimated from the operational procedures and time required to transfer these passengers to unfailed vehicles. The delay parameters must, therefore, be estimated with knowledge or assumptions regarding these procedures. No general formulation exists.

3.3.5 Determination of Passenger Delay Parameters for a Stoppage Failure Affecting Only Part of the System

3.3.5.1 General Delay Parameters. In situations where part of the system and, hence, passengers are affected by a failure, general formulations for estimating delay parameters do not exist. The analyst must examine the system for those failures which can be isolated and estimate the en route trips which will be affected by these failures. For the ith failure mode, this estimated value is referred to as PD_i. Then,

$$\overline{D}_i = \overline{TTR}_i \tag{43}$$

where: $\overline{D}_i$ = Average duration of delay for delayed passengers

$\overline{TTR}_i$ = Average downtime for ith failure.

The probability of delay can be estimated by the following expression:

$$Pr_d = \frac{\sum_i PD_i \lambda_i}{DR} \tag{44}$$

where: Pr_d = Probability of being delayed on average trip to partial system failure

PD_i = Number of passengers delayed due to ith failure

λ_i = Failure rate for ith failure

DR = Passenger demand rate.

The expected delay can be estimated by the following relationship:

$$ED = \frac{\sum_i PD_i \lambda_i \overline{TTR}_i}{DR} \tag{45}$$

where: ED = Average delay expected on average trip due to partial system failure.

(Other variables defined as before.)

3.3.5.2 Stoppage Parameters. The above relationships deal with any delay type. For determination of stoppage potential, the procedure is identical except that only failures which induce en route stoppage are considered.

3.3.6 Determination of Passenger Delay Parameters for Delays Exceeding Some Allowable Threshold

If the delay criteria are established such that some amount of delay, say Δ, is permitted before delay incidents are charged, the procedures outlines in Sections 3.3.1 through 3.3.5 are applicable if failures are defined to be failure only if $\overline{TTR}$ equals or exceeds Δ.

3.3.7 Determination of Passenger Delay Parameters for Combinations of Failure Types

Under the same assumptions discussed in Section 3.2.8, the delay parameters expected for a mix of failure types can be estimated by adding the parameters determined for each failure type. Different delay types are not additive, however, (e.g., stoppage parameters cannot be added to general delay parameters).

3.4 Short-Cut Method for Estimating Passenger Delay Parameters in Limited Situations

Many of the procedures discussed in Subsections 3.2 and 3.3 can be combined to determine system level performance measures for the following limited situations:

(1) The failure types are or can be approximated as full system stoppage types.

(2) Link loadings are relatively balanced. This results in passenger delay enveloped which are triangular in shape (refer to Station A and D of Figure 5-4).

(3) Excess capacity for delayed queue dissipation is derived solely from vehicle size.

In this situation, the graphic determination of PD* and D*, as required for station delay estimates, need not be performed. Rather, the system variables which define these (demand rate and vehicle load factor at each station) can be combined directly to form a dummy variable, α, to permit the direct computation of the probability of delay and expected delay values.

$$Pr_d = \alpha \lambda \overline{TTR} \qquad (46)$$

where: Pr_d = Probability of incurring a delay at a station

α = Dummy variable (defined below)

$\overline{TTR}$ = System level mean time to restore equipment to normal operating levels

and

$$ED = \frac{\alpha \lambda \widetilde{TTR}^2}{2} \qquad (47)$$

where: ED = Average delay at station on an average trip

$\widetilde{TTR}^2$ = System level RMS value of time to restore for failures (see Subsection 3.2.2).

In Equations (46) and (47), is defined as follows:

$$\alpha = 1 + \frac{\sum_j DR_j LF_j/(1 - LF_j)}{\sum_j DR_j} \qquad (48)$$

where: DR_j = Passenger demand rate at Station j

LF_j = Normal vehicle load factor on link downstream from Station j.

It should be noted that condition (2) above is not as restrictive as it might appear. First, the triangular-shaped delay envelope requirement does not restrict Equation (46). It only impacts validity of Equation (47). Second, considerable variation in link loading is tolerable before the passenger delay envelopes deviate significantly from the triangular shape (refer to Figures 3-3 and 3-4). Hence, if conditions (1) and (3) above are met, Equations (46) and (47) are useful for quick estimating relationships.

En route delay parameters are similarly simple to estimate. For these, the only condition required is condition (1). For this situation, the probability of delay and expected delay relationships are as follows:

$$Pr_d = \lambda TT \tag{49}$$

where: Pr_d = Probability of being delayed en route

λ = Failure rate

TT = Average en route time for average trip.

and

$$ED = TT\lambda\overline{TTR} \tag{50}$$

where ED = Average en route delay on average trip.

3.5 Determination of Total Delay Parameters

Subsections 3.2, 3.3, and 3.4 treated station delay parameters and en route delay parameters separately. These can be combined by adding if the assumption is made that any single passenger will not experience a delay, both at the station and en route in a single trip. The general formulations are

$$Pr_d = Pr_{d/s} + Pr_{d/er} \tag{51}$$

where: Pr_d = Probability of delay on average trip

$Pr_{d/s}$ = Probability of delay at a station on an average trip (Sections 3.2, 3.4)

$Pr_{d/er}$ = Probability of delay en route on an average trip (Sections 3.3, 3.4).

and $$ED = ED_s + ED_{er} \tag{52}$$

where: ED = Average expected delay on average trip (from all failures)

ED_s = Average expected delay at station on average trip (Sections 3.2, 3.4)

ED_{er} = Average expected delay en route on average trip (Sections 3.3, 3.4).

4. AN APPLICATION EXAMPLE

Section 3.0 presented the methodology for assessing passenger delay impacts of failures as a collection of optional expressions, each tailored to a selected set of system/failure type/delay type characteristics. Section 2.0 discussed the process of controlling service availability with frequent interfaces to the methodology--in particular the establishment of appropriate information to direct and execute the methodology options appropriate to the specific situation being analyzed. In this section, the relationship between the process and the methodology will be reestablished by the use of an example. This example is presented in accordance with the four life-cycle phases discussed in Section 2.0.

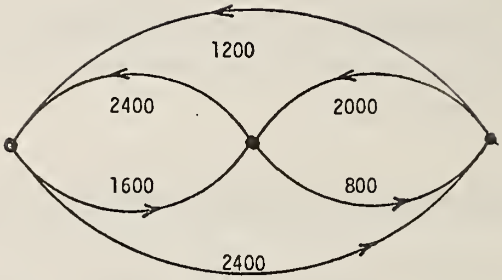
4.1 Planning and Preliminary Engineering Phase

The system being planned is very simple, designed to provide transportation service between 3 points, separated by approximately 3/4 mile. Exhibit 1 contains the pertinent demand and service parameters desired for this system.

The values used in Exhibit 1 are hypothetical. Many other factors could have been established by the Buyer, such as desired vehicle size, general guideway configuration (e.g., on-line or off-line stations), desired operational features to be invoked during a failure (e.g., ability to "shuttle" on an unfailed link), or any other factor desired. In this example, the Buyer is receptive to alternative approaches.

Establishment of Service Availability Performance Criteria

The service availability performance criteria reflect the Buyer's concerns about potential failures in the system and the impact of these failures on passenger delays, tempered by the reasonableness of these concerns with regard to both cost and feasibility considerations. Therefore, an iterative process is employed wherein the basic Buyer desires or goals are established and the methodology of Section 3.0 is used to examine the system implications. These are then examined, as necessary, to judge their reasonableness and, hence, the reasonableness of the Buyer's goals.



- Figures in above diagram are daily trip demands
- Demands are nearly constant throughout operating day
- Operating day consists of 10 hours
- Desired period of service at each station is 1.5 minutes maximum
- Desired trip time between stations is 1.5 minutes maximum

EXHIBIT 1. GENERAL TRANSPORTATION/SERVICE CHARACTERISTICS

In this example, three general delay measures are established as desired performance goals with respect to service availability.

(1) A probability of encountering a delay on an average trip of 0.04. (This corresponds to 20 delay incidents per year for an average daily user who makes 500 trips per year.)

(2) An expected delay of 0.4 minutes. (This corresponds to 200 total minutes of delay per year for an average daily user.)

(3) A probability of being stopped on the guideway, between stations, of 0.002. (This corresponds to one guideway stoppage incident per year per average daily user.)

Section 3.1 defined 10 factors which influence the relationship between system failures and passenger delays. Four of these dealt with failure characteristics.

(1) Failure type
(2) Failure rate
(3) Failure duration
(4) Failure location.

The remaining six factors dealt with the specific system application.

(5) System failure tolerance
(6) Passenger trip demands
(7) Origin-destination patterns
(8) System capacity
(9) Option for introducing additional capacity
(10) Diurnal patterns.

To use the methodology of Section 3.0, each of these factors must be defined. In this phase of the life cycle, however, little is known about most of these factors. The earlier system scenario serves to define items (6) and (7), with partial definition of item (10)--passenger trip demands are relatively constant over the operating day. Therefore, to use the methodology for assessing reasonableness of performance goals, assumptions must be made by the Buyer regarding the remaining factors. These assumptions may be quite arbitrary but should be reasonable. (The process of examining each of these factors and judicious thought about the implications of each may result in further system definition.) For example, the Buyer may wish to restrict item (9) as an option of it requires action on the part of the operator; or, he may wish to specify an ability to provide partial service in the event of a failure--item (5). Additionally, since the methodology treats "off-normal" performance, a scenario of "normal" performance must be established.

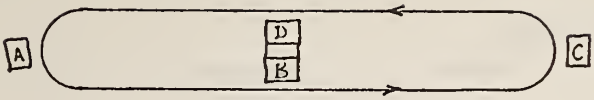
Exhibit 2 illustrates the results of these assumptions for this example. In this exhibit, the general assumptions imply a rationale of assuming "worst-case" conditions for the purposes of this reasonableness check. If the goals established do not require unreasonable values for failure rate and failure duration under these assumptions, the Buyer can be confident that his goals are achievable and could establish them as specifications for service availability performance.

At this point in the process, the methodology is invoked. Because of the nature of the assumptions used, the relationships in Sections 3.2.1 and 3.2.2 are applicable for station delays and Section 3.3.1 is applicable for en route delays. However, the assumptions provide for the possible use of the short-cut method discussed in Section 3.4. For the purposes of this example, the latter method is used. Exhibit 3 illustrates the calculations performed. In this analysis, Δ and TTR remain as variables. Equations (e) and (f) represent summary relationships between allowable failure characteristics $\overline{TTR}$, $\widetilde{TTR}$, and Δ. By evaluating these, being careful to ensure compatibility of units, and translating all time units to hours, a graph of values of $\overline{TTR}$, $\widetilde{TTR}$, and Δ can be drawn, as illustrated in Exhibit 4. The zone of acceptable values illustrated is based solely on the general Pr_d and ED criteria. To estimate the requirements for the en route stoppage goal, Equation (c) is applicable. Using the goal value of 0.002 stoppages/trip, $1/\Delta$ must be greater than 16.875 hours--depicted on Exhibit 4.

The Buyer, in conjunction with his consultants, views Exhibit 4 and all assumptions leading to its derivation. The judgments which may be applicable at this time would be as follow:

(1) The required failure rate and time to restore are not unreasonable with respect to the general delay goals. (The buyer and/or consultant may draw on experiences of existing systems which exhibit failure rates and TTR values which could meet the requirements.)

(2) The maximum failure rate determined by the en-route stoppage criteria may be difficult to achieve.



NORMAL OPERATING PARAMETERS

Origin-Destination Matrix(1)

From	To	Trips/Max Service Intervals(2)
A	B	4
A	C	6
B	C	2
C	C	5
C	A	3
D	A	6
	Total	26

Link Loading Table

From	To	Pass/Max Service Intervals
A	B	10
B	C	8
C	D	8
D	A	9

From above, four vehicles could be used, at 1.5 minute headways. Required capacity is 10 passengers. For delay calculations, 12 passenger vehicle is assumed.(3)

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(1) Derived from daily demands in Exhibit 1.
(2) 1.5 minutes from Exhibit 1.
(3) Assumption in this phase.

GENERAL ASSUMPTIONS:

- "Flat" loop configuration
- Faiures affect entire system
- Excess capacity available via vehicle size only
- All failures are of full stoppage type

EXHIBIT 2. GENERAL SYSTEM CONFIGURATION AND OPERATING PARAMETERS

- Load Factor Table

Station	Load Factor
A	10/12
B	8/12
C	8/12
D	9/12

- Using Equation (48): (All time units in terms of normal vehicle headway intervals)

$$\alpha = 1 + \frac{10\left(\frac{10/12}{2/12}\right) + 2\left(\frac{8/12}{4/12}\right) + 8\left(\frac{8/12}{4/12}\right) + 6\left(\frac{9/12}{3/12}\right)}{10+2+8+6}$$

$$\alpha = 4.385$$

- Using Equation (46) for station delays:

$$Pr_d = 4.385\lambda\overline{TTR} \qquad \text{(a)}$$

- Using Equation (47) for station delays:

$$ED = \frac{4.385\lambda\widetilde{TTR}^2}{2} = 2.19\lambda\widetilde{TTR}^2 \qquad \text{(b)}$$

- Using Equation (49) for en route delays:

$$Pr_d = \lambda TT \text{ ; where } TT = 1.35 \text{ Normal vehicle headway intervals}$$

$$Pr_d = 1.35\lambda \qquad \text{(c)}$$

- Using Equation (50) for en route delays:

$$ED = 1.35\lambda\overline{TTR} \qquad \text{(d)}$$

- Combining and equating to goals:

$$Pr_d = 0.04 = 4.385\lambda\overline{TTR} + 1.35\lambda \qquad \text{(e)}$$

$$ED = 0.4 = 2.19\lambda\widetilde{TTR}^2 + 1.35\lambda \qquad \text{(f)}$$

EXHIBIT 3. EXAMPLE USE OF METHODOLOGY DURING PLANNING PHASE

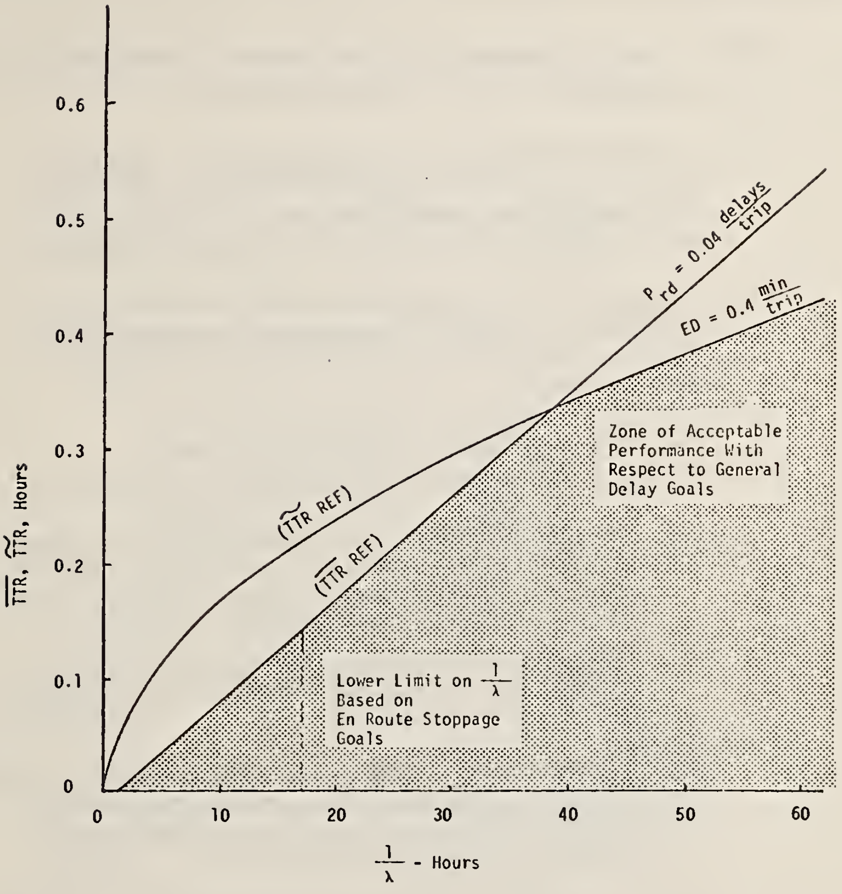


EXHIBIT 4. RELATIONSHIP OF ALLOWABLE FAILURE CHARACTERISTICS

However, the analysis was worst case. There are many simple options available to reduce the potential for en route stoppages.

Based on these, a conclusion that the goals are reasonable would be drawn and the service availability performance criteria may include other limiting factors which may or may not impact the delay analysis, but could otherwise direct the system failure performance. In this example, the Buyer is extremely concerned with stranding passengers between stations. The resulting example specifications of Exhibit 5 illustrates this.

These would become part of the system specification package. In addition, this package must contain the following:

(1) An indication that the evaluation of proposed service availability characteristics will be made using the methodology of Section 3.0, as appropriate, to the specific system proposed.

(2) A requirement for sufficient information to be provided to enable this evaluation to be made. This information consists of the following at a minimum:

  (a) A system model defining the general configuration, vehicle requirements, etc.

  (b) An operating scenario indicating the general operations under normal conditions, perturbation due to failures (general discussion of failure impacts, management strategies, operating procedures, etc.), and special characteristics of proposed system to enhance service availability.

  (c) A failure mode and delay effect analysis (FMDEA) in sufficient detail to enable the proposal evaluator to carry out the methodology (refer to subsection 2.1).

  (d) A listing of failure characteristics of major systems/subsystems which form the basis for items (5) and (6) in the FMDEA. The categories should be highly aggregated (e.g., vehicle level) and amenable to independent failure monitoring. These failure characteristics will provide the basis for system performance compliance testing.

(1) The probability of experiencing a delay due to a system failure shall not exceed 0.04 delay incidents/average trip.

(2) The average delay expected due to system failure shall not exceed 0.4 minutes delay/average trip.

(3) The probability of experiencing a stoppage incident between stations due to a system failure shall not exceed 0.002 stoppage delays en route/average trip.

(4) It is desirable to limit the duration of vehicle stoppages between stations to a maximum of 10 minutes. This shall be accomplished by incorporating the following.

    (a) On-board diagnostic/display capability for rapid fault isolation and modular design for rapid failure correction.

    (b) Manual drive capability for moving vehicles to next station. Procedure shall be consistent with safety criteria.

    (c) Tow or push capability for moving vehicles to next station.

(5) Emergency removal of passengers from failed vehicle is not considered an acceptable technique for reducing delays to passengers.

(6) In cases where the vehicle cannot be moved in a safe manner, with passengers on board, to a station area, the impact will not be considered in the delay calculations. However, the expected frequency of such occurrences shall be judgmentally evaluated. The desired goal is to eliminate such failure modes.

EXHIBIT 5. EXAMPLE SERVICE AVAILABILITY SPECIFICATION

(e) A proposed compliance test program.

(3) Calculations by which compliance with delay criteria was determined.

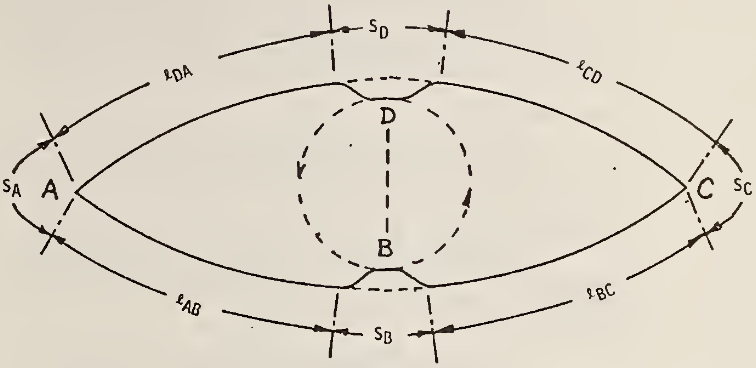
4.2 Supplier Selection Phase

During this phase, the Supplier responds, via his proposal, to the requirements established in the performance specifications. He must select his design alternatives to be consistent with the service availability specifications. He is free to use whatever techniques he feels useful in assessing the delay performance of his proposed system. However, knowing that the proposal evaluation will utilize the methodology described herein, he should, at a minimum, verify his performance utilizing the methodology. In either event, he must respond, in his proposal, to the specific information requirements established in the specifications. In this example, the Suppliers procedures are not of concern.

Rather, what is to be illustrated is the evaluation process, using the methodology described herein. Exhibit 6 illustrates the proposed configuration, subdivided into elements suitable for delay analysis. Exhibit 7 is an operating scenario for the proposed system as it might be provided in a proposal. In this operating scenario, the Supplier discusses all salient points of failure occurrence and management necessary to establish a basic understanding of the proposed system. This exhibit should not imply that this is the level of detail required. The scenario must address all service availability specifications, in particular, those specifications which are not necessarily involved in the delay calculation. Detail should be sufficient to convince proposal evaluators that criteria will be met.

Exhibit 8 is an FMDEA for this system. Note particularly Column 4 in this exhibit which divides the service effects, as necessary, to relate directly to the delay criteria, that is, delays at station, delays en route, and stops en route.

Using these data and supporting information, the methodology can be invoked with much more detail than possible during the planning phase.



NOTES:

- Solid lines indicate normal operating route
- Dotted lines indicate alternate operating routes which can be invoked to isolate certain failure effects
- Notation: ℓ_{AB} denotes link connecting station A with station B (TYP)
- Notation: S_A denotes station A (TYP)
- Four vehicles are deployed, equally spaced around system
- Vehicle capacity is 12 passengers maximum

EXHIBIT 6. GENERAL SYSTEM CONFIGURATION FOR PASSENGER DELAY ANALYSIS

Exhibit 6 identifies the system segments where for evaluation of failure service interruption effects. As illustrated, the system is designed to exhibit a high degree of fault tolerance because of its capabilities to shunt various failed segments to provide partial service while the failed segment is being restored to operable condition.

Normal Operation

During normal operation, vehicles proceed between stations in a counterclockwise direction, stopping at all stations. Vehicles are sized such that a single link contains a maximum of one vehicle at any time.

Off-Normal Operation

In case of a failure in the system, several actions are invoked automatically to reduce the service interrupting effect of that failure. In addition, capabilities are provided, to be singly invoked by the system supervisor to reduce the impact of failures.

(1) The system operating mode consists of near synchronous movement between stations. In the case of a failure anywhere in the system which is localized to one of the segments depicted in Exhibit 6, vehicles in unaffected links proceed normally to the next station and are held at that point until clearance is received to proceed. This minimizes the number of en route delays which otherwise might accrue as a result of the failure. Under normal operation, this feature also serves to maintain spacing between vehicles.

(2) Sophisticated on-board diagnostic equipment provides rapid detection/isolation of faults. Where consistent with safety considerations, resets are provided for failure mode from central control. Modular replacement capability is provided for all subsystems which are expected to fail frequently.

(3) As illustrated in Exhibit 6, alternate operating modes are provided to enable the supervisor to initiate a shunting action for central control by simply switching to one of the bepass modes. All operating and safety circuitry are automatically invoked by this action. This decision to invoke any of the alternate modes rests with the supervisor. Normally such actions would be warranted only under certain failure modes, that is, those which would be expected to last for a relatively long period of time. In our delay estimates, we have assumed these to be those failure modes with

EXHIBIT 7. OPERATING SCENARIO FOR PROPOSED SYSTEM

an anticipated failure duration of 10 minutes or greater. However, the supervisor may select other criteria as he sees fit.

When invoked, messages are automatically transmitted to stations announcing the warrantability of the portion of the system involved and requesting all passengers which would require that link to remain at that station until repairs are effected. The supervisor communicates with en route vehicles, advising passengers which require the use of the failed link to exit at the next available station.

(4) Vehicles are designed for local manual operation by appropriate personnel. Vehicles are designed with pushing surfaces at both ends. Additionally, hooks are located in the frame for attaching towing cables, if necessary.

EXHIBIT 7. (Continued)

Failure Location	Failure Type	Failure Effect on System	Failure Effect on Service: Passengers in Stations	Failure Effect on Service: Passengers Enrouta (at time of failure)	Stopped Enroute on G.W.	$\overline{TTR}$ (minutas)	λ (failures/hr)
1. Link l_{ab}	Blockage, $\overline{TTR} < 10$ min	Vehicles in all other lines move to next station and hold until system is restored	All trips	Trips from A-B and A-C in Link l_{ab}, C-A in Link $l_{c\text{-}d}$	A-B, A-C	5	.005
2. Link l_{ab}	Blockage, $\overline{TTR} > 10$ min	Shunt imposed disconnecting l_{da}, S_a, l_{ab} from system; quick action assumed so that no delays are realized by passengers on other links	All trips originating at or destined to S_a	Same as 1	Sama as 1	25	.0025
3. Link l_{da}	Blockage, $\overline{TTR} < 10$ min	Same as 1	Sama as 1	Trips from C-A, D-A in Link l_{da}; trips from C-A in Link l_{cd}, A-C in l_{ab}	C-A, D-A	5	.005
4. Link l_{da}	Blockage, $\overline{TTR} > 10$ min	Same as 2	Same as 2	Same as 3 less A-C in l_{ab}	Sama as 3	25	.0025
5. Link l_{bc}	Blockage, $\overline{TTR} < 10$ min	Sama as 1	Same as 1	Trips from B-C, A-C in link l_{bc}; trips from A-C in Link A-B, C-A in l_{cd}	B-C, A-C	5	.005
6. Link l_{bc}	Blockage, $\overline{TTR} > 10$ min	Shunt imposed disconnecting l_{bc}, S_c, l_{cd} from system	All trips with S_c as origin or destination	Same as 5 less C-A in l_{cd}	Sama as 5	25	.0025
7. Link l_{cd}	Blockage, $\overline{TTR} < 10$ min	Same as 1	Same as 1	Trips from C-D, C-A in Link l_{cd}, A-C in Link l_{ab}	C-A, D-A	5	.005
8. Link l_{co}	Blockage, $\overline{TTR} > 10$ min	Same as 6	Same as 6	Same as 7 less A-C in l_{ab}	Sama as 7	25	.0025
9. Station S_a	Blockage, $\overline{TTR} < 10$ min	Same as 1	Same as 1	Same as 3	Sama as 3	2.5	.025
10. Station S_a	Blockage, $\overline{TTR} > 10$ min	Same as 2	Same as 2	Same as 4	0	12.5	.0025
11. Station S_b	Blockage, $\overline{TTR} < 10$ min	Same as 1	Sama as 1	Same as 1	Sama as 1	2.5	.025
12. Station S_b	Blockage, $\overline{TTR} > 10$ min	Shunt around Station B	All trips at S_b	A-B in Link l_{ab}	0	12.5	.0025
13. Station S_c	Blockage, $\overline{TTR} < 10$ min	Same as 1	Same as 1	Same as 5	Same as 5	2.5	.025
14. Station S_c	Blockage, $\overline{TTR} > 10$ min	Same as 6	Same as 6	Sama as 6	0	12.5	.0025
15. Station S_d	Blockage, $\overline{TTR} < 10$ min	Same as 1	Same as 1	Same as 7	Same as 7	2.5	.025
16. Station S_d	Blockage, $\overline{TTR} > 10$ min	Shunt around S_d	All trips originating at or destined to S_d	C-D in Link l_{cd}	0	12.5	.0025
17. l_{ab}, l_{bc}, l_{co}, l_{da}	Emergency evacuation	(Not subjected to delay considerations)					.0005

EXHIBIT 8. FMDEA FOR PROPOSED SYSTEM

4.2.1 Estimation of Station Delays

The first step is to perform a unit failure analysis as described in Section 3.1. A TTR* value of 2 normal vehicle headway intervals is selected as the unit failure. Exhibit 9 shows the SRT values for each station as an input to constructing the delay envelopes of Exhibit 10.

The next step is to scale these unit failure response values in accordance with the proposed system failure characteristics. Examination of Exhibit 8 shows two basic types of failure insofar as station delay impart is concerned.

(1) Blockage failures with $\overline{TTR} < 10$ minutes
(2) Blockage failures with $\overline{TTR} > 10$ minutes.

For the first type, the system essentially stops. (Vehicles proceed to next station; however, in terms of station delays, nothing is gained from this operating characteristic (see Section 3.2.3). Hence, Section 3.2.2 is applicable. Using Equation (11),

$$Pr_d = \frac{PD^* \; \overline{TTR} \lambda}{DR \; TTR^*} \qquad (g)$$

where $\overline{TTR}$ and λ are both referenced to the total system.

Further examination of Exhibit 8 shows a high degree of commonality among TTR and λ values for a number of failure types. To enhance the calculation ease, the following substitutions are made:

λ_{L1}, $\overline{TTR}_{L1}$ - Values for typical short duration link failure

λ_{L1}, $\overline{TTR}_{L2}$ - Value for typical long duration link failure

λ_{S1}, $\overline{TTR}_{S1}$ - Value for typical short duration station failure

λ_{S2}, $\overline{TTR}_{S2}$ - Value for typical long duration station failure.

For the short duration failure, therefore, at the system level,

$$\overline{TTR} = \frac{\lambda_{L1}, \overline{TTR}_{L1} + \lambda_{S1} \overline{TTR}_{S1}}{\lambda_{L1} + \lambda_{S1}}$$

$$\lambda = 4\lambda_{L1} + 4\lambda_{S1} .$$

Station	Load Factor	SRT
A	10/12	5 TTR*
B	8/12	2 TTR*
C	8/12	2 TTR*
D	9/12	3 TTR*

Note: From Exhibit 10, the unit failure response of this system

PD* = 120 + 12 + 48 + 48 = 228 passengers delayed

D* = 120 + 12 + 48 + 51 = 231 passenger-headway intervals delay,

where

PD* = passengers delayed at stations under a full-stop failure of TTR* duration

D* = cumulative delay incurred by these delayed passengers.

EXHIBIT 9. SRT VALUES FOR UNIT FAILURE ANALYSIS

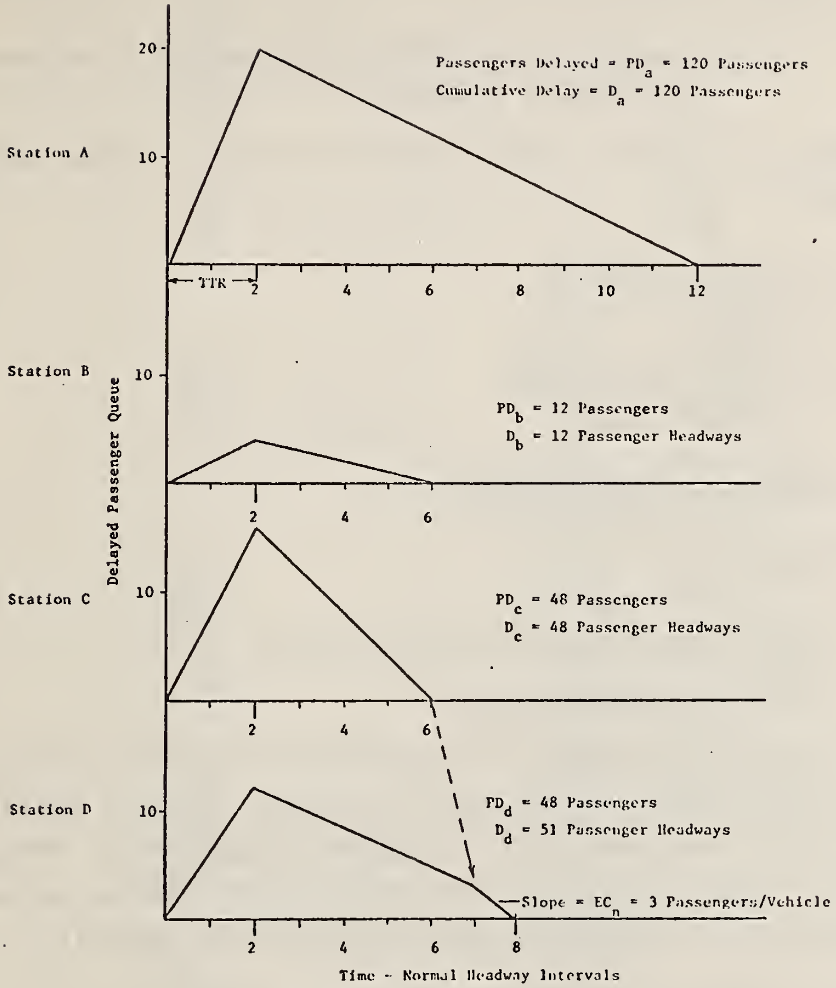


EXHIBIT 10. DELAY ENVELOPES FOR UNIT FAILURE ANALYSIS OF PROPOSED SYSTEM

By using the values from Exhibit 8,

$\overline{TTR}$ = 2.917 minutes

λ = 0.12 failures/hour.

Substituting into Equation (g),

$$Pr_d = \frac{228}{2.26} \times \frac{2.917}{60} \times 0.12$$

$$= 0.026 = \text{Probability of delay at stations due to failures with } \overline{TTR} < 10 \text{ minutes.}$$

Exhibit 11 is used to compute expected delay due to these short duration failures.

$$ED = \frac{D^*}{DR\ TTR^{*2}} \ (TTR^2)\lambda \qquad (h)$$

where

$$\widetilde{TTR}^2 = \frac{\lambda_{L1}\ \overline{TTR}^2_{L1} + \lambda_{S1}\ \overline{TTR}^2_{S1}}{\lambda_{L1} + \lambda_{L2}}$$

$$= \frac{(0.005)\ (5^2) + (0.025)\ (2.5)^2}{0.03}$$

$$= 9.375 \text{ min}^2$$

$$ED = \frac{231}{26 \times 4} (9.375)\ (0.12)\ (1/60)$$

$$= 0.042 \text{ minutes/average trip.}$$

For long duration failures, the procedures outlined in Section 3.2.6 are applicable due to the shunting capability proposed. Each of the failures ($\overline{TTR} > 10$ minutes) in Exhibit 8 could be assessed independently. However, some of these have common effects in terms of passengers affected and can be combined as indicated in Exhibit 11. Using Equations (22) and (24),

$$Pr_{d/a} = \frac{PD^*}{TTR^*\ DR} \ [(0.0075)\ (20.8)\ (19/26)\ (1/60)],$$

where $Pr_{d/a}$ = Probability of being delayed on an average trip due to a closure of Station A.

$$Pr_{d/a} = \frac{228}{2 \times 26} [0.0019]$$

$$Pr_{d/a} = 0.0083.$$

Station(1) Closed	Failures Affecting Use	Trips Affected(2)/ Total Trips	$\lambda \frac{\text{Failures}}{\text{Hr}}$	$\overline{TTR}$ min	$\widetilde{TTR}^2$ (min^2)
A	$2\ 1_2, S_2$	19/26	.0075	20.8	470
B	S_2	6/26	.0025	12.5	156
C	$2\ 1_2, S_2$	16/26	.0075	20.8	470
D	S_2	9/26	.0025	12.5	156

(1) The shunting option essentially removes a station from the system.

(2) In each case, the number of trips affected is based on all trips with origins or destinations at the "closed" station.

EXHIBIT 11. STATION DELAY FACTORS FOR PROPOSED SYSTEM

Similarly for other station closures,

$Pr_{d/b} = 0.0001$

$Pr_{d/c} = 0.0070$

$Pr_{d/d} = 0.0002.$

Combining these, the total probability of delay at stations due to a station closure can be derived.

$$Pr_b = 0.0156 \frac{\text{Delays}}{\text{Average trip}}$$

Using a similar procedure with Equations (23) and (25), expected delay calculations can be performed to yield

$ED_a = 0.095$ min delay at Station A/average trip

$ED_b = 0.003$

$ED_c = 0.080$

$ED_d = 0.005.$

Adding these,

$ED = 0.184$ min delay/average trip.

By combining the delay effects of both short and long-duration failures, the total parameters for station delays are defined.

$$\begin{aligned} Pr_d &= 0.026 + 0.0156 \\ &= 0.032 \text{ station delay incidents/average trip} \\ ED &= 0.042 + 0.184 \\ &= 0.226 \text{ minutes delay at stations/average trip.} \end{aligned}$$

4.2.2 Estimation of En Route Delays

En route delay parameters can be developed directly from the information given in Exhibit 8. First, let AB represent the number of passengers with origin at A and destination at B which would be expected to be en route on a single link at any given time. From the O-D matrix of Exhibit 2, AB = 4 passengers. AC, BC, CD, CA, and DA are similarly defined. From Columns 1 and 4 of Exhibit 8, the number of passengers delayed en route per unit time can be derived.

$$\begin{aligned}\frac{PD}{Hour} = {} & AB\,(\lambda_{L1} + \lambda_{L2} + \lambda_{S1} + \lambda_{S2}) \\ & + AC\,(5\lambda_{L1} + 4\lambda_{L2} + 5\lambda_{S1} + 2\lambda_{S2}) \\ & + BC\,(\lambda_{L1} + \lambda_{L2} + \lambda_{S1} + \lambda_{S2}) \\ & + CD\,(\lambda_{L1} + \lambda_{L2} + \lambda_{S1} + \lambda_{S2}) \\ & + CA\,(5\lambda_{L1} + 4\lambda_{L2} + 5\lambda_{S1} + 2\lambda_{S2}) \\ & + DA\,(\lambda_{L1} + \lambda_{L2} + \lambda_{S1} + \lambda_{S2})\end{aligned} \qquad (i)$$

Substituting values into this equation yields

$$\frac{PD}{Hour} = 0.685\ \frac{\text{Passengers delayed en route}}{\text{Hour}}\ .$$

In terms of probability,

$$Pr_d = 0.0007\ \frac{\text{Delayed trips}}{\text{Average trip}}\ .$$

Because the delay experienced by specific passengers due to a specific failure is equal to the TTR value of that failure, the previous approach can be used to compute expected delay. Equation (i) would take the form

$$\frac{\text{Delay (minutes)}}{\text{Hour}} = (\lambda_{L1}\ TTR_{L1} + \lambda_{L2}\ TTR_{L2} + \lambda_{S1}\ TTR_{S1} + \lambda_{S2}\ TTR_{S2}) + \ldots$$

Substituting values into this formulation yield

$$\frac{\text{Delay}}{\text{Hour}} = \frac{\text{9.83 minutes delay}}{\text{Hour}}\ .$$

In terms of expected delay,

$$ED = 0.009\ \frac{\text{Minutes delay en route}}{\text{Average trip}}\ .$$

4.2.3 Estimation of En Route Stoppage Potential

The procedure used in Section 4.2.2 is applicable here with the emphasis on passengers stopped en route (third column under Column 4 of Exhibit 8). Using these data, an equation similar to Equation (i) can be derived.

$$
\begin{aligned}
\frac{\text{PD (stopped)}}{\text{Hour}} = {} & \text{AB } (\lambda_{L1} + \lambda_{L2} + \lambda_{S1}) \\
& + \text{AC } (2\lambda_{L1} + 2\lambda_{L2} + \lambda_{S1} + \lambda_{S2}) \\
& + \text{BC } (\lambda_{L1} + \lambda_{L2} + \lambda_{S1}) \\
& + \text{CD } (\lambda_{L1} + \lambda_{L2} + \lambda_{S1}) \\
& + \text{CA } (2\lambda_{L1} + 2\lambda_{L2} + \lambda_{S1} + \lambda_{S2}) \\
& + \text{DA } (\lambda_{L1} + \lambda_{L2} + \lambda_{S1})
\end{aligned}
$$

Substituting values into the equation

$$\frac{\text{PD (stopped)}}{\text{Hour}} = \frac{\text{0.935 passengers stopped}}{\text{Hour}}$$

in terms of probability,

$$\text{Pr}_d = 0.0009 \ \frac{\text{Trips stopped en route}}{\text{Average trip}} \ .$$

4.2.4 Determination of Compliance with Specifications

By combining the results of Sections 4.2.2 and 4.2.3, overall general delay parameters can be computed.

$\text{Pr}_d = 0.032 + 0.0007 = 0.0327$ trips delayed/average trip

$\text{ED} = 0.226 + 0.009 = 0.235$ minutes delay/average trip.

These values relate directly to the criteria established in Exhibit 5, Items 1 and 2, and predict better performance than required. Similarly, the results of Section 4.2.3 relate directly to Item 3 in Exhibit 5. Again, a favorable comparison results.

4.3 Design, Construction, and Testing Phase

During this phase, the methodology would be used to assess the impact of design changes suggested by the Buyer or the Supplier. Each change considered should be reviewed to assess its overall impact on service availability.

4.4 Operation Phase

During system operation, the methodology can be used to derive appropriate and useful performance monitoring measures. There are many such measures, and the operator must select that measure which affords him the degree of sensitivity and control information desired within constraints imposed by data collection and processing costs.

The operator may select an option to compute parameters which relate to the criterial parameters; probability of delay, expected delay, or probability of en route stoppages. In this event, he would collect failure data sufficient to fill in Columns 5 and 6 of Exhibit 8 and retrace the steps outlined in Section 4.2 to arrive at performance measures. Because the delay impact of failures is dependent on the passenger trip demands and origin-destination patterns, he may also measure these and substitute them for the values estimated during the planning phase. This would enhance the relevance of performance calculation to the actual system performance.

Approaching performance measures in this fashion would yield the most insight into system performance and its constituents. Referring to the previous section, because of the building-block approach inherent in the methodology, not only is overall system performance obtained, but the major contributors to this performance are identified. These major contributors would, of course, represent high leverage control opportunities.

Alternatively, the operator may select a simpler form as a performance measure. In this example, this latter option is illustrated. The operator is faced with measuring performance with respect to three goals.

(1) En route stoppage
(2) Delays
(3) Delay duration.

By examining the relative significance of these, the operator may determine, as in this illustration, that the delay duration is less restrictive than the frequency of delays. (The system design, as illustrated in the previous section, is constrained by the probability of delay criterion and not the expected delay criterion.)

What is sought is some simple way of penalizing individual failures in accordance with their impact on (1) and (2) above. Referring back to Exhibit 8. and examining only failures of links during which the shunting option is not used, the following is derived for en route delays:

A failure in Link	AB	delays	13 passengers
	DA		18
	BC		17
	CD		14

Because the design failure rates for each of these failure modes is the same, and it is assumed that actual failure rates are approximately equal, an average number of passengers delayed per average link failure can be computed. In this case, the value would be 15.5 passengers per average link failure (with no shunt imposed).

Similar averaging techniques can be used to derive "penalty" values for other failure modes with the results shown in Exhibit 12. By applying these penalty values to failures experienced in actual operation, a cumulative penalty over some selected reporting period can be determined.

By translating the performance criteria into penalty units, a standard exists for rapid assessment of performance. Assume, for this illustration, that a desired reporting period of 2 weeks (or 120 operating hours) is established. During this period, the delay criteria of Exhibit 5 would translate into the following values:

Allowed number of passengers delayed = 5,000

Allowed number of passengers stopped en route = 250.

To utilize the monitoring technique, the failure data required would consist of

(1) Failure location (link or station with identifier, e.g., L-AB would be link A-B)

(2) The time to restore associated with this failure (TTR)

(3) A notation of shunt usage.

Exhibit 13 illustrates a hypothetical 2-week performance assessment. As illustrated by these hypothetical values, achieved performance for this period was good.

Failure Mode	Shunt Imposed?	Penalties		Station delays
		En route delays	En route stoppage	Minute TTR
Link	No	15.5	8.75	76
Link	Yes	13.25	8.75	76 $\frac{T_A}{T_T}$(1)
Station	No	15.5	8.75	76
Station	Yes	8.75	0	76 $\frac{T_A}{T_T}$

(1) $\frac{T_A}{T_T}$ = Ratio of trip affected by shunting action to total trips

Station isolated by shunting action	$\frac{T_A}{T_T}$
A	19/26
B	6/26
C	16/26
D	9/26

EXHIBIT 12. EXAMPLE FAILURE PENALTY VALUES FOR OPERATIONAL MONITORING OF SERVICE AVAILABILITY PERFORMANCE

Failure Location	TTR (minutes)	Shunt?	Penalties		Station Delay
			En route Delay	En route Stop	
S-A	3	No	15.5	8.75	228
L-AB	2	No	15.5	8.75	152
S-C	1	No	15.5	8.75	76
L-AB	15	Yes	13.25	8.75	833
S-C	2	No	15.5	8.75	152
S-C	1	No	15.5	8.75	76
S-C	5	No	15.5	8.75	380
L-CD	3	No	15.5	8.75	228
L-CD	12	Yes	13.25	8.75	561
S-C	2	No	15.5	8.75	152
S-D	1	No	15.5	8.75	76
S-A	1	No	15.5	8.75	76
S-D	3	No	15.5	8.75	228
L-DA	5	No	15.5	8.75	380
S-B	20	Yes	8.75	0	350
S-D	3	No	15.5	8.75	228
S-A	2	No	15.5	8.75	152
	Total for Period		252	140	3,986

	Achieved	Criteria
Total Delay Penalty =	4,238	5,000
Total Stop Penalty =	140	250

EXHIBIT 13. EXAMPLE OF OPERATIONAL PERFORMANCE MEASURE CALCULATIONS

Many alternatives to this exist, such as using actual delay penalties for each failure location rather than averages. The intent of this illustration was not to recommend any specific form. The operational performance measure must be <u>useful</u> to the particular operator and, hence, it must be tailored to his needs. The methodology presented in this document supports this tailoring process.

APPENDIX

REPORT OF INVENTIONS

Work under this contract did the following:

(1) Developed a methodology for helping planners of new transportation systems and writers of hardware specifications for such systems to establish meaningful requirements for service availability. See Task 3, Section 4.

(2) Developed a methodology for translating these system-level needs into hardware reliability and maintainability requirements. See Task 5, Section 5, and Task 4.

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