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Extended System Operations Studies for Automated Guideway Transit Systems

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GM Transportation Systems Center
General Motors Corporation
General Motors Technical Center
Warren, Michigan 48090

February 1982
Final Report

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US Department of Transportation
Urban Mass Transportation Administration

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16. Abstract

The objectives of the System Operations Studies (SOS) of the Automated Guideway Transit Technology (AGTT) program was to develop models for the analysis of system operations, to evaluate AGT system performance and cost, and to establish guidelines for the design and operation of AGT systems.

This final report summarizes and documents the work accomplished by General Motors and the Transportation Systems Center in the fulfillment of the Extended System Operations Studies contract. The three main areas covered in this report are: 1) the development of a set of analysis procedures that are supported by the computer models developed during the SOS project; 2) the software changes made to the Discrete Event Simulation Model (DESM) to expand and improve its capability to model guideway transit systems; and 3) the validation of the ability of the DESM to accurately model vehicle merges and the generality of modeling custom designed dispatching algorithm. Also included in this report is a description of three system level models and their possible application to the analysis of conventional transit.

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16. Abstract

The accomplishments under the Extended System Operations Studies contract are summarized in this report. The three primary areas covered are; the development of a set of analysis procedures which are supported by the simulation models developed during the AGTT-SOS project, the software changes made to the Discrete Event Simulation Model (DESM) to expand and improve its capability to model AGT systems and the validation of the ability of the DESM to accurately model vehicle merges and the dispatching algorithm used by the Morgantown PRT System.

Also included in this report is a description of three system level models developed during the AGTT-SOS program and their possible application to the analysis of conventional transit.

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PREFACE

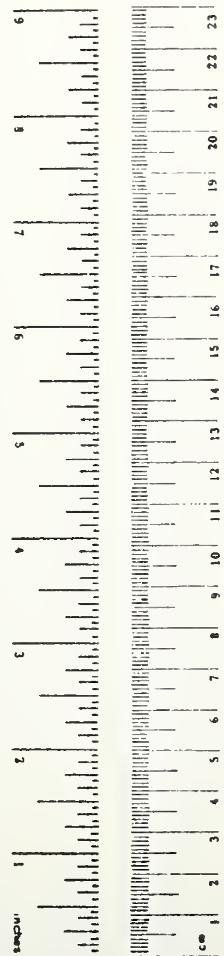
To examine specific Automated Guideway Transit (AGT) developments and concepts and to build a data base for future decision-making, the Urban Mass Transportation Administration (UMTA) undertook a program of studies and technology investigations called the UMTA Automated Guideway Transit Technology (AGTT) program. The objectives of one segment of the AGTT program, the System Operations Studies (SOS), was to develop models for the analysis of system operations, to evaluate AGT system performance and cost, and to establish guidelines for the design and operation of AGT system. This program resulted in a comprehensive set of AGT system planning and system development models. In order to maximize the benefits resulting from the availability of these models, the model research, development and analysis activity was continued by the issuance of Contract DOT-TSC-1783 in September 1979 for the Extended System Operations Studies (XSOS) to GM Transportation Systems Center.

To achieve the objectives of the Extended System Operations Studies project, the model research and development activity was continued through the implementation of software improvements and design changes to the models. Additional model validation activities were accomplished and an analysis procedure which is supported by the SOS models was developed.

METRIC CONVERSION FACTORS

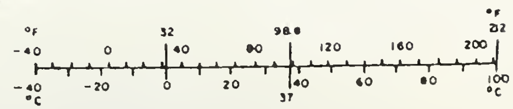
Approximate Conversions to Metric Measures

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 ACRONYMS

AFSM	Active Fleet Size Management
AGT	Automated Guideway Transit
AGTT	Automated Guideway Transit Technology
APTA	American Public Transit Association
ART	Automated Rail Transit
DESM	Discrete Event Simulation Model
DOCM	Detailed Operational Control Model
DOT	Department of Transportation
DPMS	Downtown People Mover Simulation
DSM	Detailed Station Model
FSM	Feeder System Model
GRT	Group Rapid Transit
IANDD	Input and Description
ID	Identification
IP	Input Processor
NBM	Network Build Module
PRT	Personal Rapid Transit
SAM	System Availability Model
SBARN	Station Barn
SCM	System Cost Model
SLT	Shuttle Loop Transit
SOS	System Operations Studies
SPM	System Planning Model
TSC	Transportation Systems Center
UMTA	Urban Mass Transportation Administration
XSOS	Extended System Operations Studies.

EXECUTIVE SUMMARY

A set of computer models was developed during the System Operations Studies (SOS) project for the analysis of guideway transit system operations. In order to maximize the benefits resulting from the availability of these models, the model research, development and analysis activities were continued by the issuance of Contract DOT-TSC-1783 in September 1979 for the Extended System Operations Studies (XSOS) to GM Transportation Systems Center.

The accomplishments under the Extended System Operations Studies contract are summarized in this report. The three primary areas covered are: the development of a set of analysis procedures which are supported by the computer models developed during the SOS Project, the software changes made to the Discrete Event Simulation Model (DESM) to expand and improve its capability to model guideway transit systems, and the validation of the ability of the DESM to accurately model vehicle merges and the generality of modeling custom designed dispatching algorithm.

Also included in this report is a description of three system level models and their possible application to the analysis of conventional transit.

1.0 INTRODUCTION

This final report summarizes and documents the work accomplished by GM-TSC in the fulfillment of the Extended System Operations Studies contract. Also provided in this document, is an overview of the capabilities of system level models developed during the SOS contract. In the case of the Discrete Event Simulation Model, the capabilities were subsequently augmented with additional modeling features. This effort was accomplished during the XSOS contract.

Section 2.0 of this reports provides a description of the purpose, inputs, outputs and methodology that went into the basic design of the SOS models.

Section 3.0 discusses the design modifications that were made to the Discrete Event Simulation Model. These design modifications constitute one of the major efforts of the XSOS contract. Also included in this section, is a summary of the model validation work that was accomplished as the second major effort of the XSOS contract.

Section 4.0 describes an analysis procedure developed under the XSOS contract, which is generally applicable to transportation systems. The analysis procedure, addresses the application of the SOS models to the analysis process.

Section 5.0 describes the previous applications of the SOS models to the analysis of various types of automated transit systems. This includes the analysis of actual as well as synthesized automated transit system and the application of the models during the preliminary engineering of the Detroit Downtown People Mover.

Section 6.0 discusses the results of work done under the XSOS contract in evaluating potential applications of the system level SOS models to conventional transit analysis.

Section 7.0 presents a summary of the accomplishments during the XSOS contract and an identification of the deliverables provided in fulfillment of the contract.

2.0 SOS MODEL CAPABILITIES

2.1 MODEL TYPES

The set of SOS models enables the evaluation of the performance, cost, and availability characteristics of AGT deployments. The evaluation results provide a basis for making reasonable, low-risk decisions in the selection or development of new Automated Guideway Transit Systems. The SOS models have been designed to analyze a wide range of alternative AGT system designs and application scenarios.

The computer models developed for AGTT-SOS fall into three basic categories:

2.1.1 SYSTEM LEVEL MODELS

Discrete Event Simulation Model (DESM) - A detailed simulation of the movements of individual vehicles and passengers throughout an AGT deployment using discrete event simulation techniques.

Downtown People Mover Simulation (DPMS) - A modified version of the DESM providing a direct interface with UTPS.

System Planning Model (SPM) - A simulation of AGT system operations in terms of average flow rates of vehicles and passengers.

System Availability Model (SAM) - An analytic model using equipment failure rates and simulated operations data to evaluate system availability.

System Cost Model (SCM) - An analytic model using unit costs, deployment configuration, simulated operations data, and economic factors to calculate capital, operating, and life cycle costs.

2.1.2 SUBSYSTEM LEVEL MODELS

Detailed Station Model (DSM) - A detailed simulation of the movement of vehicles and passengers in a station.

Detailed Operational Control Model (DOCM) - A detailed simulation of vehicle movements on a link, and through a merge or intersection.

Feeder System Model (FSM) - A simplified model of feeder system operation used to estimate the trips served by an AGT deployment out of a total set of transit oriented trips in an area.

2.1.3 ANALYSIS SUPPORT MODELS

A set of support programs provide the capability to build networks, display dynamic vehicle motion, queue lengths and link loading, generate deterministic demand profiles, compare summary statistics, and preprocess structured Fortran.

2.2 MODEL OVERVIEW

The overviews presented here are of those system level models most applicable to the analysis of conventional transit systems, that is, the Discrete Event Simulation Model (DESM), the System Availability Model (SAM), and the System Cost Model (SCM). Descriptions of the capabilities of the subsystem level models and the analysis support models are contained in the System Operations Studies for Automated Guideway Transit Systems Final Report.

2.2.1 DISCRETE EVENT SIMULATION MODEL (DESM)

2.2.1.1 Purpose

The DESM is a general purpose model designed to simulate:

The operation of an AGT system deployment over a complete network of guideway links and stations within a given time domain

The effects of various operational strategies and service policy options on overall system performance

Time varying demand situations

The interaction effects of vehicles and passengers competing for system resources.

2.2.1.2 Major Inputs

The major inputs are:

Network definition data which can be output from an analysis support model, or user created. The network data contains link node numbers, station entry indicators and link length for each guideway link in the network.

Station-to-station demand which can be output from the FSM, or user created. The demand data is in the form of matrices of the number of passengers traveling from origins to destinations, the associated time period, and party size information.

System characteristics data which can in part be generated by an analysis support model or entirely user created. The system characteristics data defines the system to be simulated, including, for example, the nominal speed by link or for all links, walk time for transfers, vehicle board/deboard times, vehicle capacity, route assignments, route groups, transfer list, station type, demand stop indicator, and transfer policy selection.

Runtime data, which provides the user with simulation control information such as, demand scaling information, nonzero-time data for failure/recovery instructions, and output requests.

2.2.1.3 Major Outputs

The major outputs include the following major types of data:

Station statistics

Link statistics

Completed trips data

Vehicle movement data

Station-to-station travel times

Performance summary statistics related to the overall system summaries across all links, stations, and routes and level of service measures such as operations including average travel time per completed trip.

In addition to above output and performance summary data, the DESM produces many other reports including time series listings, plots, statistical summaries and histograms. The user can choose from a large number of measures: resource utilization measures such as fleet size and total vehicle hours, performance measures such as average trip length and travel speed, and level of service measures such as average wait time and number of transfers.

2.2.1.4 Methodology

The DESM is a general purpose event model designed to simulate the operations of specified AGT systems over a complete network. The transit systems that can be modeled range from personal rapid transit (PRT) to automated rail transit (ART) using networks ranging from simple shuttles or loops to fully connected grids with guideway link combinations which include merges, diverges, and grade-separated intersections. Station representations can range from simple to complex with the specific event processes being defined by the user.

The DESM input processor transforms the network definition, trip demand, and level of service data input by the user into an internal format to provide for efficient operation of the model processor. The model processor contains the discrete event simulation architecture which provides the time dependent processing of all functions associated with trip management and station, vehicle, and guideway operations. The interaction of these operational characteristics over time can cause queues of patrons in stations and propagation of vehicle congestion on the guideway and in stations. The model processor accepts asynchronous commands for time dependent inputs such as trip requests, fleet size changes, and introduction of failures and other external stimuli. The model processor collects, summarizes and formats statistical data at user-specified intervals on the completed events, current operational status, and queues at various levels of detail (system, station, route, link, vehicle, and trip). The output processor is used to retrieve the statistical output from the model processor. The output processor also calculates simulation period performance summary measures and both prints a report and writes a file for later comparison with the results of other simulation experiments.

In the DESM, a fleet of vehicles circulates over a specified network according to a selected service policy and provides transportation service on an individual patron basis. Simulation functions associated with patrons include arrival at a station, assignment of a vehicle to service the trip request, waiting for the assigned vehicle, and boarding and deboarding. The travel portion of the patron activity is modeled in conjunction with vehicle travel. Vehicles move along the network and through stations according to a user-selected system management strategy. The strategy consists of individually selected policies for type of service, berth assignment, entrainment, empty vehicle allocation, path selection, dispatch, longitudinal control, position regulation, and merge control. Other system characteristics, such as vehicle capacity, nominal speed, and headway, are also included factors in the simulation of system performance.

The network is represented in the DESM by a set of links and nodes. A link is the model representation of a portion of the network, which connects two nodes and can be considered uniform in its characteristics.

2.2.2 SYSTEM AVAILABILITY MODEL (SAM)

2.2.2.1 Purpose

The SAM is a system-level model which provides measures of vehicle and passenger availability. Maintenance and standby fleet sizes required to support the operational fleet are also determined.

2.2.2.2 Main Inputs

The major inputs are:

Trip Logs which are produced by the DESM and contain for a non-failure reference case and for each failure case, information on vehicle and passenger travel time for each trip, travel distances, transfer time, and number of passengers for each trip.

Failure rate and maintenance time data which are produced by the user, such as failure rates by subsystem, the average time to repair and to service a vehicle, reliability, region characteristics, delay thresholds and print control cards for selected report generation.

2.2.2.3 Major Outputs

The SAM outputs are:

performance summary measures which include standby, maintenance, and total fleet size, number of service bays required, and vehicle and passenger availability.

standard reports which contain failure rates, trips delayed, vehicle delay times, passenger availability, vehicle availability and maintenance fleet requirements.

2.2.2.4 Methodology

The model provides the capability to parametrically evaluate availability measures as a function of network, system and demand characteristics by considering the effects of failure on operation, failure response strategies, hardware reliability and maintainability, and level of parts quality and redundancy.

Passenger availability is defined as the percent of total completed trips delayed less than a specified threshold. Vehicle availability is defined as the percent of total vehicle operating hours that the vehicles are not delayed by failures. The maintenance fleet is the expected number of vehicles in maintenance for regular service or failure reasons. The standby fleet is the number of vehicles needed to assure with a certain probability that a vehicle will be available to replace a failed vehicle.

Passenger availability is calculated as follows. The failure rates are specified as a function of subsystem (vehicle, station, guideway, control), cause of failure, reliability level (off the shelf, mil-standard, redundant, etc.), and failure type (stoppage, degraded operation). A standard day's scenario is described (for several distinct demand periods and regions) to establish the values of the causal variables. The causal variables used are vehicle operating hours, number of passengers through stations, system elapsed time, number of vehicles through stations, vehicle kilometers, the number of stations, and guideway kilometers. The number of passengers delayed greater than specified thresholds is determined by the SAM by comparing DESM trip logs generated for failure/recovery situations with those of the nonfailed case for the specified scenario. The trip logs contain trip origin and destination, departure and arrival times, number of transfers, and the number of people traveling together. The expected failures for the scenario are determined from the failure rate and the causal factor values. For example, the number of failures at stations is a function of the station failure rate, the passenger flow through stations, system elapsed time, the number of stations, and the vehicle flow through the station. The expected number of delays above a given threshold are calculated by multiplying the number of expected failures by the fraction of passengers delayed above the threshold for those types of failures. Passenger availability is calculated using the total number of trips and the expected number of passengers delayed above the specified thresholds. Vehicle availability is determined without regard to threshold, but rather considers the hours of delay as a consequence of failure in comparison with non failure conditions.

The standby fleet size is determined as a probability function. This probability is a function of the active fleet size, the vehicle failure rate, and the number of service bays and their service rates. A standby fleet is set to achieve a specified probability that the standby fleet is adequate, e.g., 95 percent that a vehicle will be available when required.

The average number of vehicles in maintenance (the maintenance fleet) is the number receiving routine servicing plus the number expected to be in maintenance to repair failures.

Up to five alternative reliability levels for a given system can be analyzed in a single SAM run. In addition to varying the reliability levels, the user can also specify up to ten passenger delay thresholds. Each delay threshold will have a direct effect on passenger availability by varying the number of passengers considered by the model to be significantly delayed.

2.2.3 SYSTEM COST MODEL (SCM)

2.2.3.1 Purpose

The SCM is an interpretive program that determines life cycle cost measures taking into account charges for interest, replacement, and annual operation and maintenance.

2.2.3.2 Major Inputs

The major SCM inputs include:

Data equations for the life cycle cost process.

Deployment data values representing the cost items that are site specific. These include guideway data, such as the length of elevated single lane urban guideway; passenger station data, such as the number of turnstiles in each station; support facilities, such as central control buildings; annual vehicle operations, such as number of passengers and vehicle kilometers; feeder service data, such as passengers and vehicle kilometers; and inflation factors.

System data which includes unit costs and technology items which are specific to system type. These include vehicle and guideway unit costs and vehicle propulsive unit energy.

Common data which includes costs and factors general to all systems and deployments. These include building and equipment costs, such as cost per ticket machine; nonpropulsive unit energy requirements, such as BTU/m^2/yr for air conditioning; unit pollution data, such as grams of CO per kwH; and general cost factors, such as percent of total vehicle cost for spare parts.

2.2.3.3 Major Outputs

The SCM outputs are:

The performance summary measures selected by the user.

Standard reports which provide information on land utilization, energy consumption, pollution, capital costs at purchase, cumulative capital costs to date, annualized cost, cumultive amortized cost to date, and present values.

2.2.3.4 Methodology

The SCM has a unique architecture for cost calculations. It consists of: a general purpose processor capable of performing cost modeling functions using a general purpose tree data structure, and a data base element (input) which contains the tree and tree traversal control tables which represent the equations to be used. Since the equations can be altered as a model input, several cost models can be developed by the user.

The SCM calculates the cash flow process for financing and operating an AGT system. The SCM calculates the life cycle cost of an AGT system by computing the effects of capital, operating, and maintenance expenditures throughout a specific life cycle period. Several environmental measures are also calculated by the SCM - specifically, energy consumption, pollution, and land use requirements. The SCM has been constructed so that the feeder system attributes associated with an AGT system can be included in the life cycle cost analysis.

Estimated data for input items can be varied to determine their effect on the transit system's life cycle cost. For example, the SCM is programmed so that vehicle maintenance cost is calculated by adding a cost per vehicle kilometer (for preventive maintenance), and a cost per failure (for failure maintenance) to determine a total vehicle maintenance cost. The number of failures per vehicle per year can be varied resulting in a new life cycle cost for the transit system.

3.0 SOFTWARE MODIFICATIONS

The two areas of SOS software modifications that were accomplished during the XSOS contract were related to expanding the simulation capabilities of the DESM. The modifications were, made first to improve the failure management modeling features of the DESM to reflect the failure response strategies that would be likely to be used in the application of AGT systems to Downtown People Movers and, second to incorporate a service policy representative of that employed by the Morgantown PRT System.

3.1 FAILURE MANAGEMENT

The DPM Failure Management Task developed the functional and technical requirements of the software modifications to the DESM necessary to implement an enhanced failure management modeling capability. This included the development of improved scheduled service vehicle spacing algorithms and schedule service active fleet size management modifications.

3.1.1 SCHEDULED SERVICE VEHICLE SPACING ALGORITHMS

Additional scheduled service vehicle spacing algorithms were developed and added to the DESM/DPMS in order to more effectively model the "debunching" of vehicles in congested situations, particularly after link and/or vehicle failures.

In the original version of the DESM, three vehicle spacing algorithms were implemented. Those are described below.

The first method, called "fixed schedule" launches each vehicle at a time determined by an absolute fixed time schedule which demands each scheduled launch time to be one route headway after the previous scheduled launch time. Vehicles which are behind schedule are scheduled to be launched as soon as they are ready with no additional delay. After a link failure occurs and bunching of vehicles result, this algorithm will, however, perpetuate the bunching by launching each vehicle immediately because it is behind the absolute fixed time schedule.

The second method, called "midpoint spacing" also schedules vehicle launches based on this absolute fixed time schedule. However, if a vehicle is ahead of schedule, it is only delayed half the time until the scheduled departure time. Again, if a vehicle becomes ready for launch only after the scheduled time, it is launched immediately; thus, perpetuating any bunching.

The third method, called "immediate launch", is invoked by the code when the first method is chosen while demand stop service is in effect. In this case, the absolute fixed time schedule is disregarded and each vehicle launches as soon as it becomes ready. Again, this will not result in "debunching" after failure congestion.

The two new algorithms developed as a part of this task are based on relative time schedules rather than the absolute time schedules used above. With these algorithms, if a vehicle falls behind schedule, subsequent vehicles will be delayed in order to maintain a reasonable spacing of vehicles on the route. This will result in a lower system capacity but will give a more consistent level of service to all passengers.

The first new algorithm, called "Fixed Interval Dispatch", causes a vehicle to be launched no earlier than one route headway time after the previous vehicle on the route was actually launched from the station. Vehicles ready for launch after the fixed interval are sent immediately. This algorithm accomplishes debunching after failure-caused queue formation at the first down stream station and will restore even route spacing within one cycle of the route by the first vehicle.

The second new algorithm, called "Midpoint Interval Dispatch", causes a vehicle to be launched halfway between the time it is ready and one route headway after the previous vehicle was actually launched. This algorithm causes vehicles to be launched more quickly after failure congestion than does the fixed interval case but will not restore even spacing as soon.

3.1.2 SCHEDULED SERVICE ACTIVE FLEET SIZE MANAGEMENT MODIFICATION

In the original design of the DESM and DPMS, the modeling of active fleet size changes when the scheduled service mode was used did not represent the transition period from one fleet deployment to another with sufficient fidelity for the evaluation of some operations.

The original implementation of the DESM modeled scheduled service active fleet size management by marking all vehicle trains on all routes to enter a deboard only mode, removing vehicle trains from the simulation when they become empty, and simultaneously launching an entire new fleet of vehicles equally spaced on the routes by using the same mechanism as used in launching the initial fleet. While this modeling would return the system to a steady-state operation after approximately one route cycle of the longest route, it violated many practical constraints of real systems such as the total number of vehicles available and provided an artifical continuance of service capacity during the transition period.

Because it was desired to obtain more accurate information from the DESM/DPMS concerning system performance during transition periods as well as during the following steady-state period, design changes were made to the DESM to more realistically model scheduled service active fleet size management (AFSM).

The active fleet size management algorithm was modified to model the redeployment of the vehicle fleet by using the currently active fleet (plus incremental vehicles if the total active fleet size increases) while retaining all of the modeling capabilities of the previous implementation.

The following specific capabilities were identified as desirable:

- Change number of vehicles traveling on a route
- Change vehicle train headway on a route
- Change train consist (number of vehicles per train) on a route

- Change service on one, some, or all routes
- Specify either number of vehicles on route or route headway separation
- Recalculate and maintain route spacing on a route
- Constrain total fleet size
- Place unneeded vehicles into a deboard only mode so that they become empty
- Remove unneeded empty vehicles by moving them through the network to storage areas
- Dispatch new vehicle trains from storage through the network to their assigned route
- Use station maintenance areas for train re-consisting operations
- Model the transition period and service disruption more realistically.

Two major areas of design change were made in order to implement the modified scheduled service AFSM algorithm. First, the concept of maintenance barns was developed. One or more stations in the network are labeled as maintenance barns by a new input variables SBARN. These maintenance barns require a storage link to be defined as well as one or more connecting links into and out of the storage link. The model Input Processor (IP) then calculates a designated maintenance barn for each route by an algorithm designed to pick the maintenance barn which will allow reformed trains to reach a station stop on the route in the minimum time. Given the maintenance barn for each route, the processor also chooses a station stop on the route as the station with the minimum travel time to the maintenance barn to deboard all passengers prior to sending the train to the barn.

The second major design change was the development of the concept of redeploying the existing fleet to accomplish active fleet size management rather than launching an entire new fleet. Vehicles from the existing fleet can be reassigned to other routes and/or reconsisted into trains on their own route in order to provide the new requested level of service. Reconsisting and route reassignments are accomplished at the appropriate maintenance barn. In addition, the user may specify the existence of transition vehicles for each route which are initialized and ready for entrainment at the route's barn maintenance area at the time of the AFSM event. Transition vehicles may only be specified for routes which are changing train consist or are increasing the number of vehicles. The simulation initializes sufficient transition vehicles to meet the system-wide total of vehicles needed if the user does not. The user, however, may specify more transition vehicles than needed. In this case and in the case where total fleet size decreases, unneeded vehicles are removed from the simulation at the maintenance barn storage link.

If the total number of vehicles on a route is to decrease, some trains on the route are marked for termination. A train terminates at its first station stop if it is needed by another route. In this case, the train deboards all of its passengers and is sent to the other route's maintenance barn. All passengers who deboard prematurely are treated as transfers and reboard the next appropriate train to reach their destination. If no other route needs a vehicle, the vehicle will terminate at the closest station stop to its route's maintenance barn. Also, if the train consist size on a route changes, all trains traveling the route at the old consist size terminate at the closest station stop to the route's maintenance barn. Terminating vehicles are then sent to the maintenance barn for reconsisting and relaunching on a route.

When vehicles arrive at the storage link of the maintenance barn, they are considered ready for reassignment. The vehicles are first detrained and then the existing AFSM situation is examined. Vehicles remain assigned to their original route unless they are no longer needed. If enough vehicles are available and assigned to a route, a new train is formed and scheduled to move out of the storage link to commence travel on the route. The new train is sent to the closest station stop first. If the vehicle is not needed by its current route, it is reassigned to another route, using the same maintenance barn, having the greatest unsatisfied need for additional vehicles. If this reassignment results in enough vehicles being available, a new train is formed and launched on the other route. If no such reassignment is possible, then the vehicle is reassigned to another route using another maintenance barn which has the greatest unsatisfied need for additional vehicles and is scheduled to travel to the other route's maintenance station. If no other routes have unsatisfied needs for additional vehicles, then the vehicle is removed from the simulation.

3.1.3 ENHANCED FAILURE MANAGEMENT MODELING

The original design of the DESM and DPMS includes the capability to model vehicle failures and recoveries and degraded vehicle operation. These failed vehicle occurrences were modeled in a set pre-determined manner. The modeling capabilities of the DESM and DPMS were enhanced by increasing the failure modeling detail so that a variety of realistic failure management strategies can be evaluated in terms of total vehicle and passenger delay.

A summary of the major functional requirements of the enhanced failure management modeling were:

- Provide user choice of recovery strategies
- Model failed vehicle restart by three methods
  - vehicle can be restarted
  - vehicle is pushed by trailing vehicle
  - vehicle is towed by service vehicle
- Remove failed vehicle from service to maintenance area and replace by another vehicle
- Deboard passengers from failed vehicles as transfers to reboard other vehicles
- Provide four responses for nonfailed vehicles
  - remain in revenue service
  - continue service in deboard-only mode
  - deboard all passengers and circulate empty
  - go to next station and wait for failure recovery
- Move failed vehicle at degraded speed to maintenance area
- Provide measures of failure response effectiveness.

The implementation of the enhanced failure management functions, identified above, required three major areas of design change in the DESM/DPMS. The requirement to provide the user a choice of responses is the first major design change. This implies new input variables to specify and remember the user's choice, processing to validate and report the choices, and new or modified code to carry out the modeling implied by the choices. The second major design change resulted from the composition of the enhanced responses. The new responses require several time delays (some input by the user and others calculated by the model) to be a part of the recovery process rather than the previous method of utilizing a user-specified failure time and a user-specified recovery time. The resulting design then required that the response choices and time delays be remembered for future processing rather than be immediately executed as before. This design resulted in new variables and new and modified code segments.

The following input is required to specify the failure, the response, the associated time delays, and the response parameters needed by the enhanced failure management strategies:

- Failure Specification Card
  - Time
  - Location
  - Type of Failure
  - Degradation Factor
  - Delay to Detection
  - Recovery Method
  - Delay to Restart
  - Delay to Replacement
  - Recalculate Minimum Path
- Other Vehicle Response (By Route)
- Tow Vehicle Path
- Tow Vehicle Speed Degradation Factor
- Maintenance Barn Identification.

Table 3-1 describes the steps that occur in the three restart strategies, Table 3-2 describes the actions taken by the simulation to effect the other vehicle responses. These can be specified by route in the scheduled service case. The default specification is to remain in revenue service.

No new statistics or measures were created as a result of the enhanced failure modeling. However, additional output messages were generated to document the time-series nature of the new failure responses. One or two line messages are reported by the model processor as each failure event occurs. These messages include vehicle ID's, link numbers, link entry or exit, and time of event occurrence for the various events. The events include vehicle capture, failure detection, vehicle restart, push coupling begins, tow path becomes clear, vehicle reaches maintenance area, replacement vehicle available, and replacement train dispatched.

These new messages when combined with the existing vehicle and passenger travel statistics provide all the information needed for analyzing the effects of failure conditions and alternative failure responses in a network scenario.

TABLE 3-1. DEGRADED VEHICLE RESTART STRATEGIES

RESTART

- Vehicle scheduled to restart at user input time delay after detection

PUSH BY TRAIL VEHICLE

- At detection time, if vehicle queued behind failure, entrain and schedule restart at user input coupling time delay after detection
- If not, whenever next vehicle queues behind failure, entrain and schedule restart at user input coupling time delay after current time
- At beginning of coupling time delay, failure minimum path table becomes active

TOW BY SERVICE VEHICLE

- Calculate travel time along path and apply speed degradation factor
- Check if path is clear
- Close links and stations merging into tow path
- If on-line station is on path, preserve one and only one path through station
- When path clear, schedule restart

TABLE 3-2. OTHER VEHICLE RESPONSES (BY ROUTE)

- Continue revenue service
  - No action

- Deboard only mode
  - Vehicles marked as deboard only at detection time
  - Board event bypassed
  - Vehicle unmarked at restart time

- Empty circulation mode
  - Vehicles marked as empty circulation at detection time
  - All passengers deboard at first station stop
  - Board event bypassed
  - Vehicles bypass subsequent station stops
  - Vehicles unmarked at restart time

- Wait in station mode
  - Vehicles marked to wait in station at detection time
  - Vehicles wait prior to board event
  - At restart time, vehicles unmarked and prompted to perform board event

3.2 DESM MODEL VALIDATION

The objective of the DESM Model Validation task was to ascertain the degree of credibility the user may place upon model generated data and statistics in light of the assumptions and modeling simplifications that have been designed into the DESM. In particular, this validation effort addressed the means by which vehicle travel on a guideway link and the merging of two vehicles from separate guideway links onto a single link are modeled and if these modeling techniques in any way adversely affect the credibility and usefulness of the DESM output information. The question of model validity that was addressed was the fact that the DESM models vehicle travel across a guideway link as a series of discrete events when, in fact, vehicle travel is in practice a continuous process.

The general methodology applied to the DESM validation was as diagrammed in Figure 3-1.

The general procedure followed in the validation task was to compare vehicle flow through a merge junction as modeled by the DESM to that as modeled by the Detailed Operational Control Model (DOCM). The DOCM is a continuous model completely independent from the DESM and developed as part of the System Operations Studies program specifically for the purpose of investigating the detailed dynamics of vehicles traveling on guideway links and merging at intersections.

The premise was made that if the DESM and DOCM vehicle travel data through the intersection compared favorably with regard to (1) travel time through the junction and (2) the sequence in which vehicles effect the merge, then the modeling approach taken within the DESM as well as any simplifications or assumptions built into the merge algorithms do not detract from the overall confidence that the model user can have in the DESM output data. The general process used to make the comparison of travel times and merge sequences between the DESM and DOCM was as outlined in Figure 3-2.

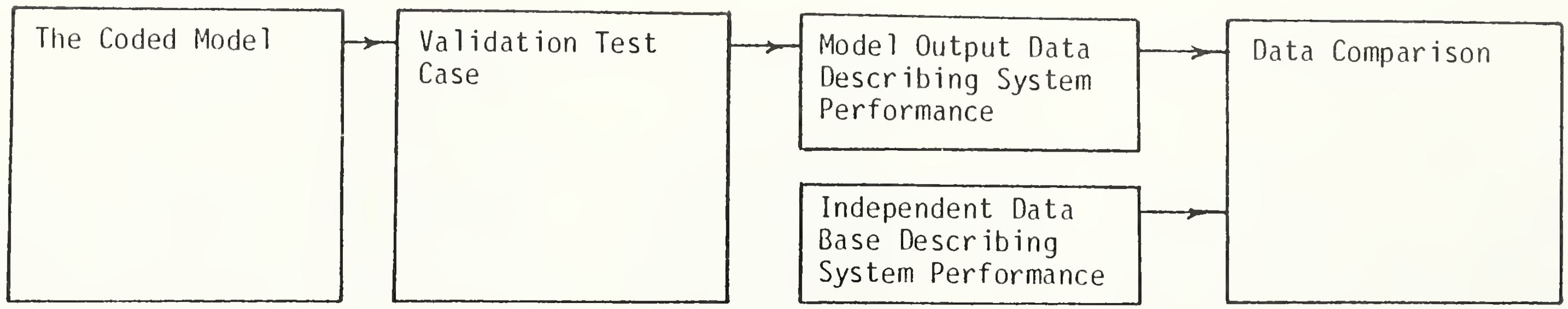

FIGURE 3-1. FLOW DIAGRAM OF THE GENERAL VALIDATION METHODOLOGY

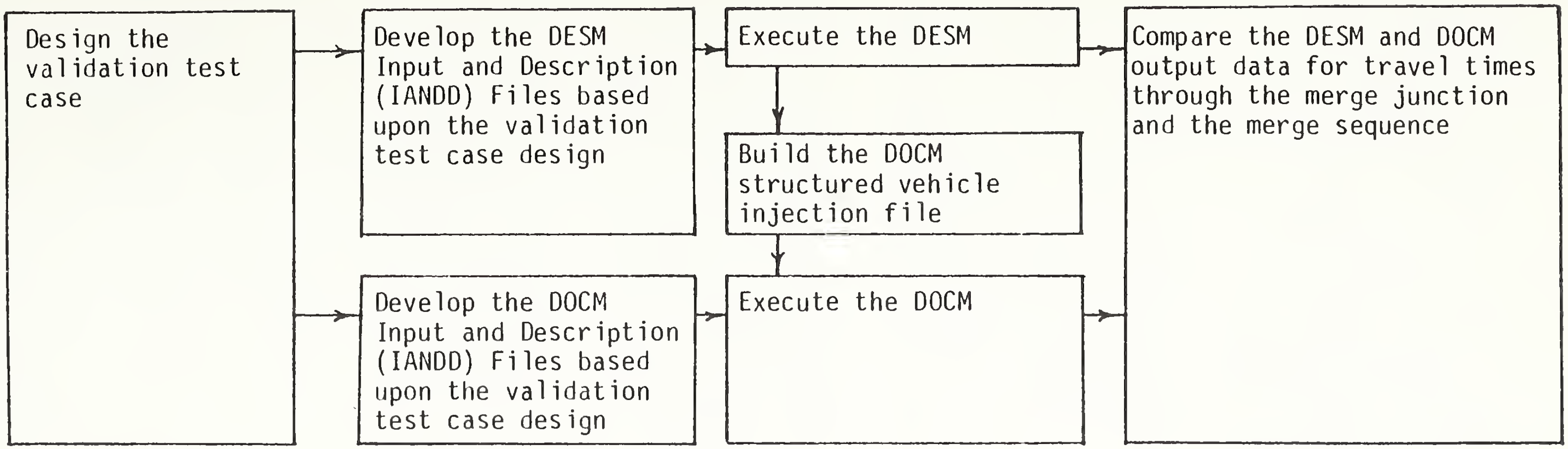

FIGURE 3-2. FLOW DIAGRAM OF THE DESM VALIDATION PROCESS

It was concluded from the results of the validation test case experiments performed that the DESM models the process of vehicle travel in the vicinity of guideway merge junctions in sufficient detail and with sufficient accuracy that for vehicle flow densities below 70 percent of the junction's theoretical capacity no compensation is required. At higher density levels, the basic DESM modeling approach degrades. This degradation can, however, be adequately compensated through the use of the heuristic merge table which was designed into the DESM.

3.3 TIMEOUT/GROUP DEMAND RESPONSIVE SERVICE VALIDATION

The objective of the Timeout/Group Demand Responsive Service Validation task was to demonstrate that the DESM could be used to model a service mode operation similar to that in use at the Morgantown, West Virginia PRT installation, and to validate the DESM using actual operation data.

Preliminary effort toward this objective was accomplished by developing the appropriate DESM input files to model a specific two-hour period of operation at Morgantown PRT and then by executing the model using these files. The resulting DESM output regarding vehicle dispatch times was then compared to actual vehicle dispatch times for the corresponding time period at Morgantown.

The results of this comparison indicate that to the extent that data was available for actual system operation, the DESM as modified can accurately duplicate the vehicle dispatch process as seen at Morgantown PRT.

4.0 ANALYSIS PROCEDURE

The analysis procedure task developed an analysis approach for the design of AGT systems wherein the combinations of parameter values which can influence the design and for which tradeoff analyses need be performed are grouped into three basic categories. The three categories of analyses relate to different levels of design specification. The consideration of parameters within each of the three categories corresponds to a separate phase of analysis of AGT system deployments. The three phases of analysis which are described in the procedure are initial system definition and screening, trade-off analyses, and sensitivity analyses. The initial system definition specifies the basic system parameters which define alterntive system concepts. The trade-off analyses considers the evaluation of other system parameters which represent major alternatives within a given system concept. The sensitivity analyses discusses the evaluation of the system level impacts of variations in still other system parameters.

The initial system definition phase of the analysis identifies deployment alternatives which merit further analysis. Deployment alternatives are defined in terms of basic parameters such as vehicle class (Personal Rapid Transit (PRT), Small Vehicle Group Rapid Transit (SGRT), etc.), service policy, and network configuration. A deployment alternatives screening procedure is described to limit the number of different deployments to be analyzed in subsequent analyses.

The initial system definition analysis establishes an approach to defining application areas, demand, networks, and routing strategies for scheduled service. Where a specific application of AGT technology is to be evaluated, the required data for representation of site-specific details of the application area is discussed. The procedures that were followed for the Systems Operations Studies to select and define representative application areas for analysis using the SOS software, to define and model candidate networks, and estimating procedures for AGT demand using the SOS software are discussed.

The second major area covered in the initial system definition process was the analysis of major subsystems to determine characteristics and relationships necessary to support the system analysis. Guidelines for the definition of major subsystems and data and equations for calculating characteristics of AGT vehicles such as dimensions, performance, energy utilization, and noise generation are presented. Equations for calculating minimum headway and a procedure for estimating control system cost parameters are also presented. Alternative operational control strategies which can be modeled using the SOS software are defined. Guidelines for sizing AGT stations, derived from analysis using the Detailed Station Model (DSM) and the Discrete Event Simulation Model (DESM), are presented. The cost model is discussed and representative cost data are presented. A procedure for conducting an availability analysis including the generation of subsystem reliability data, the selection of representative failure events, the evaluation of failure consequences using the DESM, and the evaluation of system availability using the System Availability Model (SAM) is presented.

A procedure for quickly evaluating system deployments, the final step in the first phase of the analysis, was developed. The purpose of the initial deployment screening is to limit the scope of subsequent more detailed analysis by eliminating from further consideration deployment alternatives which were clearly inferior.

A second category of system design parameters to be analyzed as a part of the analysis procedure were also identified. These parameters represent major alternatives within a given system concept and include empty vehicle management strategies for demand responsive service and the number of cars per train by route for scheduled service. The effects on system performance, cost, and demand of alternative values of parameters in this category were evaluated in trade studies. The output of this phase of the analysis is to provide a set of system deployments which satisfy performance requirements in a cost effective manner. Thus, the systems are well defined in terms of their performance, cost, and availability characteristics. Guidelines for conducting system trade-off analyses are developed in the procedure.

The final category of system design parameters to be evaluated as a part of the analysis procedure consists of a relatively large number of parameters which are amenable to independent variation within a narrow range of values. These parameters, which include cruise speed, dwell time, vehicle capacity, and unit cost values, are varied parametrically in a sensitivity analysis to characterize their impacts on system performance and costs. The results of these sensitivity analyses are used to define an optimum configuration for each of the system deployments under investigation.

Figure 4-1 illustrates the manner in which the SOS processors are used to support the analyses in the analysis procedure. The figure shows the general flow of data from one part of the analysis to another. Each of the three stages of analysis includes some or all of the analyses depicted in Figure 4-1.

The uses of the SOS software in support of the analysis procedures were also defined under this task. The initial system definitions begin with demand generation and subsystem analysis. After a set of deployment concepts are identified, the Feeder System Model (FSM) is used to generate station-to-station demand matrices for each deployment. Inputs to the FSM include zone-to-zone origin-destination demand data, a network description in terms of station coordinates relative to zone centroid locations, feeder system charcteristics, and an estimate of station-to-station trip time for the deployment under consideration. The Input Processor of the DESM is then used to generate the AGT system performance estimate. Before this data is input to the FSM, the analyst must add to each entry an estimate of initial wait time at the AGT stations. The output of the FSM includes station-to-station demand matrices for all demand periods. These matrices serve as direct inputs to the Discrete Event Simulation Model (DESM).

The network description used in the Feeder System Model (FSM) for demand generation can be converted to DESM input with the aid of the Network Build Module (NBM). This interactive graphics program accepts station location and network connectivity data and produces the network file which is input directly into the DESM.

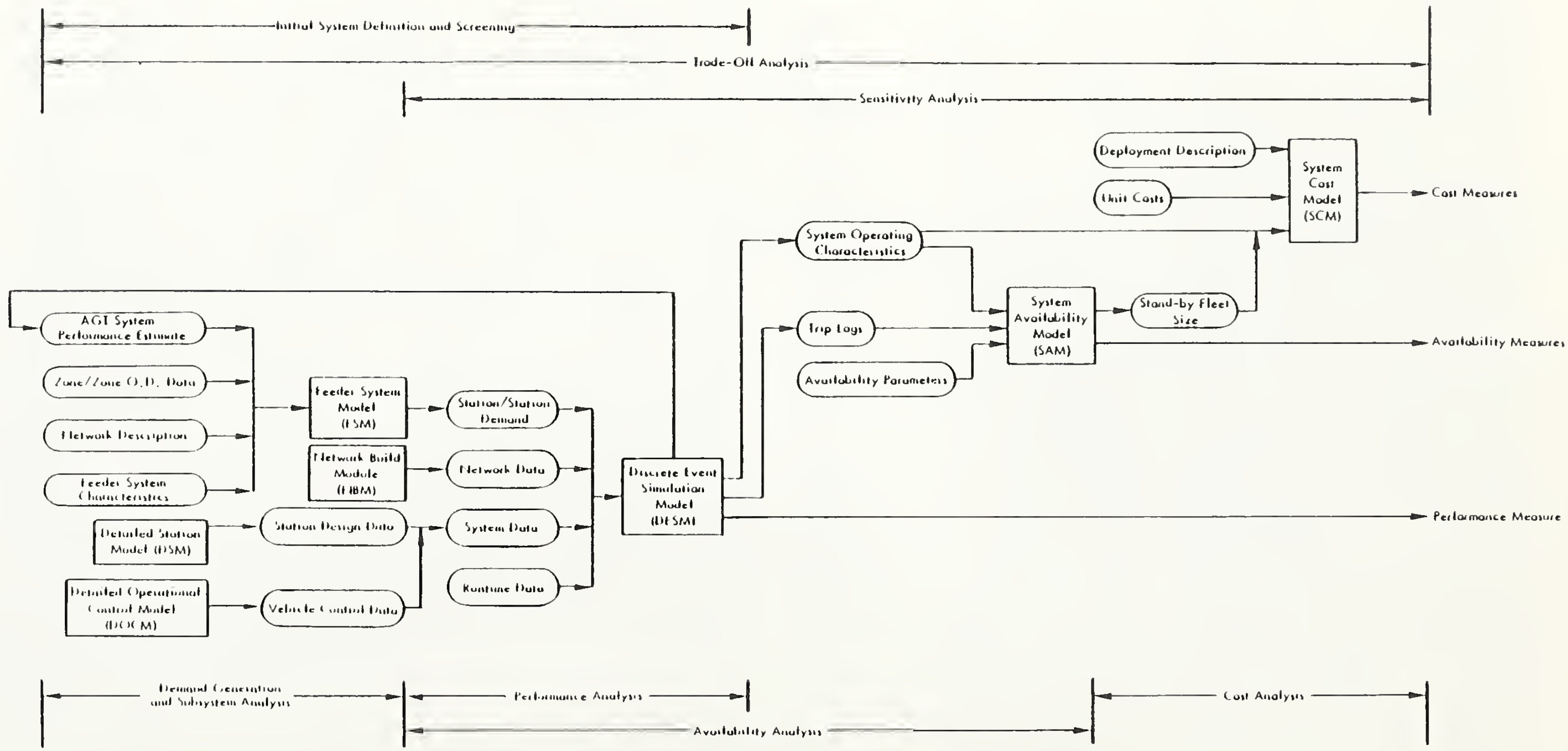

FIGURE 4-1. USE OF AGTT-SOS SOFTWARE FOR SYSTEM ANALYSIS

The Detailed Station Model (DSM) is used in the subsystem analysis to investigate flows and queues of both vehicles and passengers in on-line or off-line stations.

The Detailed Operational Control Model (DOCM) is used in other subsystem analyses to evaluate minimum headway requirements and vehicle control alternatives.

The results of the subsystem analyses are used in the development of system data for input to the DESM. The DESM evaluates performance measures which are used in screening the deployments to identify the ones which have potential for satisfying system goals and are worthy or more detailed analysis.

In the trade-off analysis, the DESM is used to determine the combinations of vehicle capacity, train consist, and operating headway which satisfy the wait time and performance goals for major demand periods of the service day. The size of the operating vehicle fleet is the major independent variable in the process of matching the performance of each deployment with the performance goals. The system configuration which satisfies the performance goals at approximately minimum cost is selected as the nominal configuration for each deployment. System costs are evaluated using the System Cost Model (SCM). In addition to capital and variable costs, the SCM also evaluates land utilization, energy consumption, and air pollution. Required inputs to the SCM include system operating characteristics based on DESM outputs, standby fleet size generated by the System Availability Model (SAM), and system description and unit cost information supplied by the analyst. Trade-offs of major system parameters are made by comparing performance and cost measures for the nominal deployments. In this way the overall system effects of various parameters are considered in each trade-off. If the performance of the nominal system is significantly different from that initially estimated, the demand generation process is repeated using the best available estimates of system performance. Then, using updated demand estimates, system sizing and performance analyses are repeated to define nominal system characteristics.

System availability analysis involves the use of both the DESM and the System Availability Model (SAM) to evaluate the consequences of failures on system performance. The DESM is used to generate vehicle and passenger delay information relating to various failures. A trip log (a file containing a record for every completed trip) is generated by the DESM and used as direct input to the SAM to evaluate the number of passengers delayed by individual failures. Output statistics generated by the DESM are used by the analyst to calculate vehicle delay data and system operating characteristics for input to the SAM. The SAM also requires input parameters such as failure rates and mean time to repair. The SAM generates measures of system availability and the standby fleet size required to achieve those values of availability.

Sensitivity data can be generated by varying the values of input parameters for each processor independently or the combined use of models may be required when performance, cost, and availability are evaluated.

5.0 APPLICATION OF SOS MODELS

The SOS models have been utilized for the performance, cost and availability analysis of a broad range of actual and potential applications of automated guideway transit. These analyses have considered, various system types such as, personal rapid transit (PRT), group rapid transit (GRT), and automated rail transit (ART); varying demand levels, and a number of different network configurations. Extensive analysis of shuttle loop transit (SLT) systems have also been accomplished using the SOS models. Table 5-1 provides the general characteristics, of the types of systems that have been analyzed and the actual implemented system of which these characteristics are considered to be representative. Table 5-2 lists the types of application scenarios that served as the basis for performing the analysis.

In addition to the above applications of the software within the SOS contract, the models were also used during the preliminary engineering phase of the Detroit Downtown People Mover project to provide performance and cost comparisons for the network configurations which were under study for implementation.

TABLE 5-1. GENERALIZED SYSTEM CHARACTERISTICS

Category	Class	Subclass	Service Type	Minimum Traveling Unit Capacity (Passengers)	Maximum Operating Speed (km/hr)	Characteristic Minimum Headway (s)	Example System
PRT	PRT	low speed	non-stop	3-6	13-54	3 or less	Cabinentaxi
		high speed	non-stop	3-6	55+	3 or less	CVS
GRT	SGRT	low speed	multiple-stop	7-24	13-54	3-15	Morgantown
		high speed	multiple-stop	7-24	55+	3-15	UMTA-AGRT
	IGRT	low speed	multiple-stop	25-69	13-54	15-60	Airtrans
		high speed	multiple-stop	25-69	55+	15-90	Unimobile Transporter
	LGRT		multiple-stop	70-109	13-54	50-109	SEA-TAC
ART	ART		multiple-stop	110+	55+	60+	WMATA

Legend

PRT - Personal Rapid Transit
GRT - Group Rapid Transit
SGRT - Small Vehicle GRT
IGRT - Intermediate Vehicle GRT
LGRT - Large Vehicle GRT
ART - Automated Rail Transit

TABLE 5-2. TYPES OF APPLICATION SCENARIOS

SYSTEM TYPES		DEPLOYMENT SCENARIO								
		LOW SPEED							HIGH SPEED	
		ACTIVITY CENTER LINE-HAUL	ACTIVITY CENTER CIRCULATION	CBD CIRCULATION			CBD LINE-HAUL		METRO AREA HIGH CBD HIGH REVERSE	METRO AREA LOW CBD HIGH REVERSE
				LOW DEMAND	MEDIUM DEMAND	HIGH DEMAND	LOW DEMAND	HIGH DEMAND		
SLT	SGRT						L1			
	IGRT		LMC	SS	L1, L2	L1				
	LGRT	PS				L1	LM, L1	L1		
ART									LH	
GRT	SGRT									G
	IGRT								LH	

PS - PARALLEL SHUTTLE
SS - SERIAL SHUTTLE
L1 - ONE-WAY LOOP
L2 - TWO-WAY LOOP
LC - COLLAPSED LOOP

LM - SIMPLE MULTIPLE LOOP
LMC - COMPLEX MULTIPLE LOOP
G - GRID
LH - LINE-HAUL

6.0 POTENTIAL APPLICATION OF SOS MODELS TO CONVENTIONAL TRANSIT

The SOS and Extended SOS work was entirely concerned with the modeling and evaluation of automated transit systems. However, the software and techniques developed are sufficiently general that they should be applicable to most forms of conventional transit as well. The main constraint on the use of the simulation software is that vehicles within the model move over fixed pathways. This need not be construed to mean that only fixed guideway systems such as light rail can be modeled. A set of fixed bus routes also fits this condition.

The other modeling software does not deal with explicit representations of the individual elements of the system link specific route paths but rather uses more parametric representations like total routes miles, average failure rates or number of daily operations, etc. Thus, this software should be directly applicable to any system which can be represented by those parameters.

6.1 SUMMARY OF SOS MODEL CHARACTERISTICS

6.1.1 DISCRETE EVENT SIMULATION MODEL (DESM)

The purpose of this simulation model is to represent the operation of a transit system in terms of vehicle and passenger movements. This representation has enough detail to allow the observation of individual vehicles and passengers. However, it is efficient enough that periods of operation long enough to aggregate dependable statistics can be simulated. In general, the ratio between real time and simulation time will fall between 100:1 and 10:1 depending on the size of the fleet and number of passengers being simulated. (A larger fleet with many passengers implies a slower simulation.)

To model a system in the DESM requires three sets of input data.

A representation of the paths available to vehicles within the system in terms of nodes and links interconnecting those nodes. This data include identification and detailed configuration of nodes which function as stations or passenger access points.

A set of system equipment operating characteristics. This data includes items such as vehicle capacities, link travel speed limits, dispatching and scheduling constraints, boarding and deboarding delay functions, and a set of routes defined on the network.

A matrix of the passenger demand on the system at the network stations. The demand being modeled can vary with time both in overall magnitude and in the spatial distribution of demand among the stations.

In general, the structure of the system network, and the demand being imposed on the system are defined in input data files rather than being designed into the simulation. A variety of policies for dispatching vehicles and maintaining separations between them is available within the program. The size of the system which can be simulated is limited by practical considerations of computer memory size and run time rather than any inherent constraints within the software. For convenience in performing trade-off studies such as evaluating alternative vehicle sizes and route densities, most of the input data can be varied at runtime without completely redeveloping input files. For instance, operating speeds on some links could be changed to study the impact of a large construction project on the operation of a bus route passing through the affected area.

Application of the DESM to any system using fixed guideways with a limited number of stations (e.g., a subway system) is straight forward. The only difference being the need for representing manual rather than automatic operation. For rail systems, a block system for maintaining safe vehicle separations is normal in either automatic or manual operation and thus at the level of detail used in the DESM there is no real distinction necessary.

Light rail systems operated manually can have quite different characteristics from those anticipated in automated systems. First, these systems usually depend on the operator to maintain separation particularly when operated at grade and mixed with other traffic. Second, stops to pickup and discharge passengers can be very frequent and these stops, at least superficially, do not resemble formal stations. Finally, when operating at grade and mixed with other traffic, operating speeds are affected by a variety of extraneous factors like other traffic and traffic controls. These characteristics require some ingenuity to model since they are not directly represented within the DESM. Human maintenance of vehicle separation's resembles the operation of a vehicle follower control system which is an option in the DESM. Individual performance varies far more than with automatic controls, but for a relatively large sample these differences should not significantly degrade the overall system statistics developed. The representation of individual stops as stations is quite possible but depending on the system size may prove impractical. One possible alternative which may be considered in this event is to lump several stops into one node. To do this would require that the station dwell time in the lumped node and the travel time over the links connecting those nodes be made artificially large so that the resulting travel from one node to the next would be sufficiently accurate for statistical purposes. This lumping of access nodes will also make the demand matrix more tractable in size. Since delays in boarding and deboarding can be made a function of the total number of passengers involved, no artificial manipulation of this portion of station dwell time need be performed.

The modeling of travel speed in a mixed traffic at grade system is a more complex problem. If the purpose of a study is to observe detailed interactions of the system vehicles with infringing traffic, and traffic controls no good modeling mechanism exists within the DESM. However, if the purpose is to evaluate the system wide effects of constricted through put on links, then it is likely that assigning low speeds to the links involved will be adequate. Or, more accurately, the effect of the infringing traffic on transit vehicle performance may be modeled by introducing standard deviations to individual link speeds. Use of the DESM at this detailed level may be included as an added option to the model.

If the effects of traffic quantization by stop lights is of interest, a limited model of this might be achieved by establishing nodes at the traffic lights and superimposing the traffic light timing pattern on the headway zone as an optionally added processing. Use of the DESM at this detailed level of modeling is recommended only if it is suspected that effects such as these are having large consequences over all. Modeling in terms of low average speeds across links should generally be sufficient to develop reliable statistics on system operation or, more importantly, changes in those statistics due to changes in either operating policies or road conditions.

Bus systems introduce another variation from the design purpose of the DESM in that they apparently do not utilize a fixed guideway. However, for modeling purposes, the route structure of a bus system is equivalent to the network of a fixed guideway system. One could view a city street map as the network but this would be unnecessarily complex since only those streets actually used by the buses are needed. If, however, it is known a priori that certain alternative streets are likely to be considered as alternatives these could be entered for later convenience since it is not necessary that every network link be used by a route structure under consideration.

Once the basic network has been defined, a bus system has most of the characteristics discussed previously for light rail at grade mixed traffic modeling. The main new item to be considered is the ability of busses to pass one another as a normal operating procedure. To model this capability, it will be necessary to introduce artificial redundant bypass links at points in the route structure where this will happen in normal operation. Another method would be to model stops as off-line stations so that busses can pass through without stopping if desired. For most normal operations this should not pose any great limitations on the accuracy of the results of a simulation. It is felt, however, that using the DESM for modeling bus breakdowns in operation is not likely to be effective, where for fixed guideway systems this is a highly useful technique since one stopped vehicle can propagate stoppages over large parts of a fixed network rather quickly by blocking a heavily used link.

6.1.2 SYSTEM AVAILABILITY MODEL (SAM)

The purpose of the SAM is twofold. Given inputs defining equipment and vehicle failure rates, causal factors, failure consequences and system operating statistics, the SAM estimates system availability in terms of the probability that the average passenger will complete a trip without being delayed more than some threshold value. A secondary calculation in the SAM estimates the number of spare vehicles required to ensure that a specific operating fleet size will be available. This calculation uses data on average service times, number of available maintenance bays, preventive maintenance policy, vehicle failure rates and system operating statistics to calculate the needed fleet of spares over a range of probabilities that replacements for failed vehicles will be available.

Since the representation of a system in this model is parametric rather than explicit it is relatively independent of the system type. What is required for the availability computation is a table of failure consequences (in terms of passenger delays) for areas of the system and times of day generated either by hand or through use of the DESM and a table of causative factors (like vehicle operating hours or miles of travel) partition in a similar manner. The fleet size computation allows the number of available maintenance bays and assumed routing maintenance policy to be easily varied so that trade-off studies of the consequences of enlarging maintenance facilities can be performed.

6.1.3 SYSTEM COST MODEL (SCM)

The purpose of the SCM is to aggregate system costs (both capital and operating) in a time phased manner so that system life cycle costs can be calculated. The system representation is a set of three tables defining unit costs, quantities of units making up the system, and a set of general economic factors to be applied. System elements can be defined to have varying useful lifetimes and associated with each is an end of life value. Again since the representation of the system is independent of the type of control system or operating policy, this model can be applied to any system type. To provide further generalization within this model, it has been configured as an interpretive processor. This allows the set of equations processed to relate unit costs and quantities and to perform the life cycle and economic factor calculations to themselves be an input file. Thus, it is possible to completely revise the calculations in this model within very broad limits without new programming. One use of this ability which has been made was a study of the trade-off between system cost and reliability as more expensive MIL Spec parts were substituted for commercial grade electronics in a control system. The modifications made were to simultaneously aggregate subsystem failure rates and costs from tables of part cost, failure rates, and part utilization in the subsystems. The set of equations existing in the present version of the SCM are covered in detail in the SOS "System Cost Model User's Manual" (EP-78170).

6.2 GENERAL APPLICATION APPROACHES

Throughout the following discussions, it will be assumed that a calibrated demand model exists on the area under study. This is necessary for any investigations of usage or revenue sensitivities to changes in route structure or service level. However, if this is not the case, the Feeder System Model (FSM) within the SOS software can be used to provide rough estimates of demand sensitivities. This model operates on a representation of demand which is distributed geographically and maps it onto the entry and exit points of a transit network. It is assumed that the demand is all transit oriented in that it will use the transit mode if at all reasonable. Thus, it gives a relative measure of the demand which a particular route structure can capture. Level of service is factored in through use of a diversion curve operating on the total travel time for a trip using transit as compared to that for an assumed alternate mode. Clearly, the accuracy of the absolute results are highly dependent upon the basic transit oriented demand representation and the assumption made as to the performance of the competing modes. However, the FSM if calibrated to current system performance will provide useful relative data on alternative system deployments. That is, it can indicate whether demand capture is likely to increase or decrease in response to changes in a transit system.

6.2.1 OPERATIONS PLANNING

To apply the SOS software operations planning or alternatives evaluations for a property, the major preliminary effort will be the development of a data base representing the system network. For a rail, or other fixed guideway system this can be a relatively straight forward node and link representation of the various guideway segments. As discussed under the DESM summary, systems with many stops for passengers rather than more widely spaced stations will require that trade-offs between model fidelity and computer usage be made. The number of points at which passengers can enter or leave the system will affect not only the network storage size but the size of the demand matrix to be developed. Since demand is represented in an O/D matrix, storage and processing time for demand varies as the square of the number of access points. This consideration leads to the suggestion that the system network be represented where practical as a set of psuedo station nodes each of which is either a route stop or an aggregate of a few. Areas of particular sensitivity or interest like a CBD could be modeled in detail while the remainder of the network data base might well evolve into a lumped node representation of the entire network and a set of detailed subnetworks which could be substituted for one or more psuedo nodes as desired for a particular analysis.

In parallel with the network data base, a calibrated demand model of the metropolitan area of interest should be established. It would be desirable from an analytic point of view for this model to be maintained, recalibrated and updated on a regular basis, perhaps on an annual or bi-annual basis. This model will be used iteratively with the system performance simulation to establish projected usages for alternatives being considered. At present, SOS does not have a method for projecting revenues so some estimating method should be developed which can take demand estimates and derive revenue estimates. This could be accomplished with the SCM with some minor modifications.

Another data set which is required is the cost model input tables of unit costs, system definition, and economic factors. The SCM is sufficiently general in its present configuration that most cases should be covered by a redefinition of variables. However, a property might find it a useful task to develop an equation definition file specific to that property to be included in the cost model portion of the data base.

Finally, a file will be developed defining the system characteristics. These include route definitions, operating speeds, vehicle sizes and a set of operating policies covering the number of vehicles per route, train consists, and schedule and dispatching policies. The data in this file will be the most commonly varied to test operational methods.

The final step in setting up the models should be a validation run against some standard set of data covering one or more hours of manual operations. This run serves a dual purpose. First, it will establish confidence in the model performance and second it will provide a base line for future evaluations of alternatives.

The process which can be used to evaluate changes in system operations is straight forward. First the data base files are called up and modified to include the desired changes. In the case of system data these changes can be made at run time. For network alterations, some prior manipulation using the SOS graphic support software may be needed to develop new networks and route data files. When the model of the altered system is ready, it is simulated using the DESM. This generates the needed data for input to the SCM, demand, and revenue models. If the changes result in significant changes in demand, the DESM run should be repeated using the new demand matrix to test for significant changes in level of service which might affect the demand model. This iteration of simulation and demand models should lead to a state of equilibrium at which time new costs can be generated in the SCM and final evaluation of the operating policy being tested can be made.

6.2.2 MIXED MODE OPERATION EVALUATION

An illustrative scenario for the use of SOS techniques is a situation similar to the Miami case with a rail rapid transit (RRT) line feeding a CBD circulator. The characteristics of the RRT are essentially fixed with the major variable being the frequency and loading of arriving trains at the interface stations. The CBD circulator is assumed to be a guideway system using small vehicles at relatively close headways. The purpose of the investigation is to determine the appropriate circulator fleet size and scheduling to optimize the total system performance and to identify potential for the sectors including demand levels at which system performance starts to degrade.

This evaluation needs the same initial data base identified in the preceding section in operations planning. However, in this case the representation of demand at the DESM input will be held constant and the level of service optimized to handle that demand. In the last stages of the study, overall demand magnitude can be varied by changing one variable to test the sensitivity of the final design to demands beyond the design point.

Scheduling and fleet size variations can be handled by changing a few input variables to the DESM and resimulating. The technique recommended is to establish a nominal configuration in the DESM and SCM input files and developing a base set of operating statistics and costs for that case. Changes can then be made in variables defining fleet size, scheduling, operating policies, vehicle sizes and demand magnitude or any other system characteristic and rerun made to establish performance and cost sensitivities to the parameters. In general these changes require only that new values for the selected variables be supplied at runtime initilization with the input processor handling the conversion of those values into the form needed by the simulation automatically.

Once the trends of the various operating statistics have been established, those changes which result in improvements can be pursued to the point of diminishing returns. To do this effectively, the SCM should be rerun for each new system configuration so that any performance improvements achieved can be evaluated for cost effectiveness.

A final step in this study would probably be to configure a conventional bus circulation system in place of the fixed guideway system and compare performance and costs between the two. If desired, the same optimization process can be applied to this alternative system configuration before making comparisons.

6.2.3 MAINTENANCE FACILITIES PLANNING

The SOS System Availability Model (SAM) has two major functions. The first is to calculate the performance reliability of a system as perceived by an average user in terms of his probability of completing a trip with no failure induced delays. The second is to calculate the standby fleet size needed. This latter calculation considers average vehicle failure rates, nominal peak period operating statistics, preventive maintenance practices, average vehicle repair rates, the number of repair bays available and the desired operation fleet size. From this data, a table showing the expected number of vehicles under repair and the needed standby fleet for a user selected range of probabilities that a replacement vehicle will be available when an operating vehicle fails.

Each of these input variables can be changed independently. By using the SCM (an SCM modification or a separate calculation), many questions on the sizing of maintenance facilities and the desirability of changing routine maintenance policies can be investigated. One can compare the capital investment in facilities needed to improve meantime to repair performance against the additional cost of standby vehicles for the same improvement in replacement vehicle availability. Given an estimate of failure rate decrease due to more preventive maintenance one can trade-off such policy changes against fleet or facilities enlargement. If failure rate improvements can be achieved by use of higher cost parts, the cost effectiveness of the approach can be tested.

The data base needed for this use of the SOS techniques includes the previously discussed SCM input data, average vehicle failure rates, average vehicle repair times, frequency and duration of scheduled maintenance, and statistics on normal operations in terms of average vehicle mileage or operating hours per unit time, etc.

6.2.4 PERFORMANCE COMPARISONS

An interesting application of the SOS techniques which is a variation of the mixed mode study discussed in paragraph 6.2.2 is the comparison of automated and manual operation of the same fixed guideway facility. The same approach of establishing a baseline configuration and evaluating its performance cost and availability keeping some normal demand representation as a fixed input can be used.

The major modeling differences between manual and automatic control lies in the selection of a policy to maintain vehicle separation around a route in the automatic case. It may also be necessary to tailor the control policy if a specific automated system is to be modeled. To assure a meaningful comparison, cost differences (both capital and operating) and reliability differences must be fully defined. These differences include the obvious elimination of the operating crew and the addition of control equipment as well as changes in such things as maintenance crew size requirements and average elapsed time before recovery of a failed vehicle.

In all such comparisons, it is vital that as many variables as possible held constant between systems so that differences in performance can be attributed to the system characteristics rather than extraneous items. It is for this reason that it is recommended that an identical trip list be used as input to all runs to minimize performance differences due to random changes in passenger arrival times, etc. An extension of this reasoning would suggest that both systems being compared be independently optimized before comparisons are made since techniques which work effectively for one system type many not be applicable to the other.

7.0 SUMMARY

The XSOS program consisted of the following eight (8) tasks:

Task 1 - New Scenario Analysis
Task 2 - Analysis Procedure
Task 3 - Software Update
Task 4 - Workshops
Task 5 - Failure Management Modifications
Task 6 - DPM Implementation Report
Task 7 - Technical Reviews and Final Report
Task 8 - Universal Service Strategy.

Task 1 consisted of two validation efforts, 1) the validation of the merge modeling accuracy of the DESM, and 2) the replication of the dispatching characteristics of a Morgantown type system using the DESM for the purposes of testing the models generality and validating the model against actual operational data. These efforts were concluded with the issuance of the DESM Validation Final Report No. EP-81055 and the Timeout/Group Demand Responsive Service Algorithm Validation Report 04-I-810011.

The Analysis Procedure, Task 2, included the development of a procedure for analyzing AGT systems using the SOS developed models, a Memo Report on the Evaluation of UMTA Service Dependability Measures and a Memo Report on the Limitations of the SPM. Task 2 was completed with the issuance of Procedure For The Analysis of Representative AGT Deployments, Report No. GP-80071, Evaluation of UMTA Service Dependability Measures Using SOS Software, Memo Report SOS-F-800036, and Memo Report, Use And Limitations Of The SOS System Planning Model (SPM), J. Thompson to A. Priver, dated August 14, 1980.

The development and delivery of the code and updated DESM User's and Programmer's Manuals to include the DOT-TSC required changes to the DESM and the Failure Management and Morgantown Modifications was accomplished in fulfillment of Task 3. The code was supplied in the form of a magnetic tape containing the latest version of the DESM. The DESM/DPMS modifications developed at DOT-TSC and implemented by GM-TSC are documented in Memo Report SOS-F-800057. The User's Manual was updated to describe the new functions, define the core requirements, and describe the new input and output functions. Operating procedures were updated, new error messages added, new routines included and output reports revised to reflect the modification made to the user's manual. The Programmer's Manual update included the core memory requirements and revision of the code segment tables to include the new members. The new global variables were included as were new debug flags. The logic tables were revised, new routines added and old routines updated. The update of these two manuals was provided in the form of a set of revision pages for each manual.

Task 4 consists of the GM-TSC participation in two workshops on the capabilities and applications of the SOS models and the accomplishments of the XSOS program. Support of and participation in Workshop I was accomplished in December, 1979. The completion of the remainder of this task will occur in September, 1981 with the GM-TSC participation in the APTA Committee Meeting on System Operations Studies Technology. Here, presentations will be given on the Analysis Procedure (Task 2) and the Application of the SOS models to conventional transit.

The documentation of the Failure Management Modifications was accomplished under Task 5. Three memos were published which describe the functional and technical requirements of the software modifications. These include memos on the implementation of an enhanced failure management capability, scheduled service vehicle spacing algorithm, and scheduled service active fleet size management. The documentation was provided as an attachment to the memo dated 10 October 1980 from R.A. Lee to Dr. Arthur S. Priver.

The installation of the DPMS software at APL in January, 1980 along with the software documentation fulfilled the requirements of Task 6.

Task 7 consisted of five (5) technical reviews presented by GM-TSC on the financial and technical status of the XSOS program. A presentation overview, results, conclusion and action items were documented for each technical review and provided in memo form to DOT-TSC along with copies of all materials presented. This final report concludes the remaining effort to be accomplished under this task.

Two efforts were included within the scope of Task 8. These consisted of, 1) the software design and documentation necessary to enable a programmer to implement the universal service strategy concept described in, "Proposal for Implementation of Universal Service Strategy Simulation Software", EP-80002 into the DESM software, and 2) the development of examples of conventional transit applications where the system level models (DESM, SCM and SAM) developed during the SOS/XSOS programs, could be used to study and/or investigate performance cost and availability trade-offs. The software design and documentation effort was accomplished through a two (2) day technology transfer meeting held at GM-TSC with DOT-TSC personnel on July 28 and 29, 1981. The application of the SOS models to conventional transit effort will be completed with the presentation of results at the APTA Committee Meeting on System Operations Studies Technology.

APPENDIX

REPORT OF NEW TECHNOLOGY

The work performed under this contract, while not expected to lead to any new invention, has led to the development of several computer models and an analysis procedure for evaluating the guideway transit system operations using these models. The models and the analysis procedure may be and have been used for the transit analysts to understand the impact of transit operations on transit performance so as to improve the transit productivity and operational efficiency.

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