eport No. UMTA-MA-06-0048-80-11

EXTENDED SYSTEM OPERATIONS STUDIES FOR AUTOMATED GUIDEWAY TRANSIT SYSTEMS

PLAN FOR TASK 5 -- DPM FAILURE MANAGEMENT

GM Transportation Systems Division
General Motors Technical Center
Warren, MI 48090

APRIL 1981
FINAL REPORT

Prepared for

U.S. DEPARTMENT OF TRANSPORTATION
URBAN MASS TRANSPORTATION ADMINISTRATION
OFFICE OF TECHNOLOGY DEVELOPMENT AND DEPLOYMENT
OFFICE OF NEW SYSTEMS APPLICATIONS
WASHINGTON, D.C. 20590

Technical Report Documentation Page

1. Report No.
UMTA-MA-06-0048-80-11

2. Government Accession No.
PB 81-210569

3. Recipient's Catalog No.

4. Title and Subtitle
Extended System Operations Studies for Automated Guideway Transit Systems; Plan for Task 5, DPM Failure Management.

5. Report Date
June 1981

6. Performing Organization Code
DTS-723

7. Author(s)
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8. Performing Organization Report No.
DOT-TSC-UMTA-80-28

9. Performing Organization Name and Address
General Motors Corporation*
GM Transportation Systems Center
GM Technical Center
Warren, Michigan 48090

10. Work Unit No. (TRAIS)
MA-06-0048

11. Contract or Grant No.
DOT-TSC-1783

12. Sponsoring Agency Name and Address
U.S. Department of Transportation
Urban Mass Transportation Administration
400 Seventh Street, S.W.
Washington, D. C. 20590

13. Type of Report and Period Covered
Final Report
Nov. 1978 - June 1981

14. Sponsoring Agency Code
UTD-40

15. Supplementary Notes
*Under contract to:
U.S. Department of Transportation
Research & Special Programs Administration
Transportation Systems Center
Cambridge, Massachusetts 02142

16. Abstract

The purpose of Task 5 in the Extended System Operations Studies Project, DPM Failure Management, is to enhance the capabilities of the Downtown People Mover Simulation (DPMS) and the Discrete Event Simulation Model (DESM) by increasing the failure modeling detail of these processors so that a variety of failure management strategies can be evaluated in terms of total vehicle and passenger delay. The purposes of this planning document are to list the major failure management strategies that are currently being considered in engineering studies of DPMs and to propose software modifications, in functional terms, and analysis techniques that will permit modeling of as many of these strategies as possible.

The existing failure management strategies in the DESM/DPMS are detailed first and then failure management strategies that have been considered in detail by DPM planners and engineers in Los Angeles, St. Paul, and Detroit DPM systems are presented. The software modifications necessary to implement the various strategies are described and assessed for feasible implementation within the allocated task resources. Software modifications that would permit the modeling of most of the strategies identified in the report are recommended. Some of the recommended changes are of a general nature that would enhance the capabilities of the DPMS and DESM to model failure-free system operation. The final section of this plan presents the schedule and an estimate of project resources required to complete the task.

17. Key Words
Downtown People Mover (DPM) Modeling
DPM Simulation
DPM Planning
Failure Management
AGT Technology
Discrete Event Simulation Model
DPM Software
AGTT Operations Program

18. Distribution Statement
Available to the Public through the National Technical Information Service, Springfield, Virginia 22161.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	**Unclassified**	34	A03

Form DOT F 1700.7 (8-72)

Reproduction of completed page authorized

Technical Report Documentation Page

1. Report No. UMTA-MA-06-0048-80-11	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Extended System Operations Studies for Automated Guideway Transit Systems - PLAN FOR TASK 5 -- DPM FAILURE MANAGEMENT		5. Report Date June 1981 6. Performing Organization Code DTS-723
7. Author(s) [illegible] J. F. Duke and R. A. Lee, GM TSC		8. Performing Organization Report No. DOT-TSC-UMTA-80-28
9. Performing Organization Name and Address GM Transportation Systems Center* General Motors Corporation GM Technical Center Warren, Michigan 48090		10. Work Unit No. (TRAIS) UM033/R0726 UM041/R0725 11. Contract or Grant No. DOT-TSC-1783
12. Sponsoring Agency Name and Address U.S. Department of Transportation Urban Mass Transportation Administration Office of Technology Development & Deployment Office of New Systems Applications Washington, D.C. 20590		13. Type of Report and Period Covered Final Report Nov. 1978 -June 1981 14. Sponsoring Agency Code UTD-40

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16. Abstract

The purpose of Task 5 in the Extended System Operations Studies Project, DPM Failure Management, is to enhance the capabilities of the Downtown People Mover Simulation (DPMS) and the Discrete Event Simulation Model (DESM) by increasing the failure modeling detail of these processors to encompass a variety of failure recovery strategies. In this report the current capability of the DPMS and DESM to model vehicle stoppage and degradation failures is reviewed. Possible failure response strategies, including ones that have been considered by DPM planners and engineers, are described in terms of alternative responses for vehicles and passengers. Software modifications necessary to implement the various strategies are described, and the feasibility of implementing each strategy in the software within the allocated task resources is assessed. Software modifications which would permit the modeling of most of the strategies identified in the report are recommended. Some of the recommended changes are of a general nature which would enhance the capabilities of the DPMS and DESM to model failure-free system operation.

17. Key Words Failure Management DESM/DPMS Modeling Capabilities	18. Distribution Statement DOCUMENT IS AVAILABLE TO THE PUBLIC THROUGH THE NATIONAL TECHNICAL INFORMATION SERVICE, SPRINGFIELD, VIRGINIA 22161

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	36	

Form DOT F 1700.7 (8-72)

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PREFACE

The Automated Guideway Transit Technology (AGTT) System Operations Studies (SOS) program, sponsored by the Urban Mass Transportation Administration (UMTA), has resulted in a comprehensive set of AGT system planning and development models. In order to maximize the benefits resulting from the availability of these models, through their continued use and improvement, GM Transportation Systems Center (GM TSC) has been awarded a contract by the Transportation Systems Center of the U.S. Department of Transportation. The objectives of this effort are to enhance the usefulness of the AGTT-SOS software through continued research and development activity, to increase user familiarity of and confidence in the software through information dissemination workshops and further validation, and to extend the guideline standards and requirements for design and operation of AGT systems.

This Plan describes alternate failure response strategies and the software modifications required to model them in the DPMS and DESM. Specific software modifications are recommended to enhance the failure management modeling capabilities of the DPMS and the DESM. Work performed under this task was supported by the UMTA Office of Technology Development and Deployment, Office of New Systems Applications. The Technical Monitor for the project at DOT/TSC was Arthur Priver, who was assisted by Li Shin Yuan.

This document was prepared under the direction of the Extended SOS Program Manager at GM TSC, James F. Thompson. The report was written by John F. Duke and Ronald A. Lee of GM TSC. John Duke was responsible for the final preparation of the report.

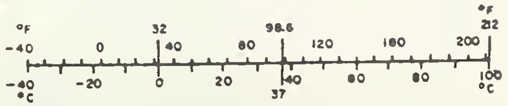
METRIC CONVERSION FACTORS

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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1.0 INTRODUCTION

The purpose of the DPM Failure Management task is to enhance the modeling capabilities of the DPMS and DESM by increasing the failure modeling detail of these processors so that a variety of failure management strategies can be evaluated in terms of total vehicle and passenger delay. The purposes of this planning document are to list the major failure management strategies that are currently being considered in engineering studies of Downtown People Movers and to propose software modifications, in functional terms, and analysis techniques which will permit modeling of as many of these strategies as possible.

The existing failure management strategies in the DESM/DPMS are detailed first and then failure management strategies which have been considered in detail by DPM planners and engineers in Los Angeles, St. Paul, and Detroit DPM systems are presented. The software modifications necessary to implement the various strategies are described and assessed for feasible implementation within the allocated task resources.

The final section of this plan presents the schedule and an estimate of project resources required to complete the task.

2.0 CURRENT FAILURE MODELING

The DESM and DPMS are general purpose discrete event simulation processors used to model the actions and interactions of automated guideway systems such as Downtown People Movers. The failure and failure response models provided in the DESM/DPMS are generalized to represent a variety of failure and degradation situations. However, it is possible to model more specific failure management strategies through a moderate level of code modification to the DESM/DPMS.

Failures can be specified by the DESM/DPMS user for any of the entities listed below:

1. Guideway links - either entry, exit, or the entire link
2. Station links - either entry, exit, or the entire link
3. Stations - the entire station is failed by not allowing entry to the input ramp and exit from the output ramp; movement on other station links continues.

These are not vehicle failures, as such; however, they can be interpreted as vehicle failures because the first vehicle to encounter the failure condition stops, and subsequent vehicles queue behind the stopped vehicle exactly as if the vehicle itself had failed. In the case of guideway link failures, the minimum path algorithm is re-executed with an artificially high travel "cost" on the failed link in order to reroute future paths around the failed link, if possible.

Vehicle degraded operation may also be specified by defining a guideway link entry or exit where the next vehicle to pass will go into degraded operation. In this case, the degraded vehicle "limps" to the closest station, deboards all of its passengers, and disappears from the simulation.

The user of the model specifies the time duration of a failure by giving a failure recovery time. At recovery, vehicles are restarted and continue their operations as if no failure had occurred. Degradation is in force until a user-specified degradation recovery time or until a vehicle enteres degradation mode, whichever occurs first. The following table sumarizes the effects of failures and degradations on the vehicle fleet and the set of passengers in the current DESM/DPMS.

1. Failed vehicle
   - Vehicle stops.
   - Passengers remain on-board.
   - At recovery vehicle restarts and continues as if no failure had occurred.

2. Degraded vehicle
   - Vehicle travels at reduced speed to closest station.
   - All passengers deboard as completed trips (a constant penalty time is added to the trip time of those passengers who have not reached their desired destination).
   - Vehicle is removed from the simulation.
   - No vehicle spacing adjustment is made for scheduled service.

3. Other vehicles
   - Vehicles continue in normal service as if no failure or degradation occurred.
   - If a link is blocked, an alternate path, as determined by minimum path algorithm, is followed.
   - If no alternate, vehicles queue until recovery releases blockage.
   - No passengers are deboarded prematurely.
   - No stops are skipped unless an off-line station is blocked; then, passengers who miss destination are deboarded at the next stop as completed trips (a constant penalty time is added to the trip time of those passengers who have not reached their desired destination).

3.0 GENERAL SOFTWARE IMPROVEMENTS FOR FAILURE MODELING

While the generalized failure and degradation processing present in the DESM/DPMS provides an acceptable model for failure occurrences, it became apparent during AGTT-SOS analyses that the recovery models are too simplistic to model particular recovery strategies in detail. Therefore, the following areas have been identified for software modification in order to better model failure and degradation recoveries in more general cases.

The current dispatch algorithms under scheduled service do not result in an effective debunching control after queue buildup resulting from either a failure or congestion. A related problem is that there is no slack time built into the schedules. Route spacing headways are based on minimum travel times and minimum board-deboard times. Therefore, once a vehicle falls behind schedule, it remains behind schedule. Vehicle spacing by fixed schedule dispatch requires that each vehicle be dispatched one headway time from scheduled launch time of the previous vehicle dispatched on the route. The vehicles are always trying to maintain a theoretical fixed schedule. If vehicles fall behind schedule because of a failure or congestion, they are launched without delay in order to try to catch up to schedule. However, since there is no slack in the schedule, they are unable to catch up, and so they continue to be launched from each station without schedule delay. Thus, any bunching that occurs during the failure is perpetuated under the fixed schedule dispatch.

Two independent software modifications are recommended to improve the fixed schedule dispatch algorithm. First, the ability to add slack to the route spacing schedules will be added to the software by specifying a minimum dwell time at the station that is larger than the minimum board-deboard time. This minimum dwell time modification will be coordinated with the changes DOT-TSC has made in the board-deboard calculations. With slack in the schedules, vehicles will be delayed at stations during uncongested operation until scheduled dispatch time thus decreasing system capacity, but they will be capable of catching up to schedule through a series of undelayed dispatches following a failure condition.

The second software modification, independent of the first, would define an additional fixed schedule dispatch, called fixed separation dispatch. In this algorithm, vehicles would be scheduled for dispatch one route headway behind the actual previous dispatch on the route rather than the scheduled previous dispatch. This algorithm would limit capacity since any vehicle delay would ripple back through the entire fleet. However, the algorithm would maintain an almost constant separation among the vehicles on the routes, and it would effect a rapid debunching after congestion due to failure.

The currently implemented midpoint schedule dispatch algorithm attempts to avoid bunching by specifying the scheduled dispatch time as the midpoint of the actual departure time of the previous vehicle and the next fixed schedule departure time. This is an ineffective dispatch algorithm after a failure because vehicles are still trying to catch up to a theoretical fixed schedule which assumes no failures. This algorithm would be effective at maintaining reasonable spacing in a noncongestion situation in a schedule including slack because it would moderately respace vehicles which run ahead of schedule.

We also recommend a third software modification, independent of the first two, to define an additional midpoint dispatch, called midpoint separation dispatch. In this algorithm, vehicles would be scheduled for dispatch midway between the actual departure time of the previous vehicle and the current time plus one route headway. This algorithm would effect an orderly debunching of vehicles following a failure or congestion situation while maintaining more system capacity than the fixed separation dispatch algorithm described above.

The implementation of these software modifications would provide the DESM/DPMS user eight schedule dispatch combinations instead of the present two as shown below.

Dispatch Algorithm	Slack in Schedule	Currently Available
Fixed schedule	Yes	No
Fixed schedule	No	Yes
Fixed separation	Yes	No
Fixed separation	No	No
Midpoint schedule	Yes	No
Midpoint schedule	No	Yes
Midpoint separation	Yes	No
Midpoint separation	No	No

The current implementation of active fleet size changes does not effectively model the replacement of a degraded vehicle in scheduled service. A degraded vehicle will disappear from the simulation at the first station encountered but a replacement can only be entered as an active fleet size change. However, for scheduled service active fleet size changes, a whole new fleet of vehicles is started while existing vehicles go into a deboard-only mode and are then removed from the simulation. While this implementation is marginally acceptable to model scheduled service fleet size changes if data from the transition period are noncritical, the transition period following a failure and subsequent replacement vehicle launching is likely to be important; therefore, the need clearly exists for an improved algorithm. Assuming that an adequate debunching algorithm is implemented for scheduled service dispatch, the need to dispatch an entire new fleet of vehicles will be obviated. A much simpler active fleet size change algorithm can be implemented which only recalculates scheduled route parameters, such as number of vehicles on the route and route headway, and relies on the dispatch algorithms to relieve any bunching effects which result from a changed number of vehicles on a set cycle period route. Software modifications will also be implemented to model the transition from one consist size to another on a route.

The additional scheduled dispatch algorithms can be added to the existing code as options selected by the user and can be coded entirely within existing variables. The addition of a minimum dwell time parameter for stations will likely introduce a new variable and will generate changes in both input and model processor code segments. The changes in active fleet size management will require extensive study of existing code to identify the effects of these functional changes.

4.0 ALTERNATIVE FAILURE RESPONSE STRATEGIES

The failure management strategies which are being considered by DPM planners and engineers[1,2,3] include various failed vehicle recovery alternatives, strategic location of turnbacks and sidings, and the ability to reconfigure network operation. Since failures which result in vehicle stoppage or degradation are most disruptive to network operation and passenger service, these types of failures and detailed system responses to them are important areas of concern. The UMTA DPM guidelines[4] identify the following failed vehicle recovery strategies which should be considered in the design of DPM systems:

1. Automatic operation restart
2. On-board manual control
3. Towing or pushing by another revenue vehicle
4. Towing or pushing by a guideway service vehicle
5. Hoisting from the guideway

Several of these alternatives were analyzed in detail in conjunction with network alternatives, such as turnbacks and a maintenance siding, in the context of the proposed Los Angeles DPM system.[5] In this analysis the relative effects of the various failure recovery strategies in terms of passenger delays were determined analytically. The potential value of a detailed simulation in the evaluation of system impacts was noted.

The DESM or DPMS, coupled with the System Availability Model (SAM) are valuable tools which can be used to evaluate the effects of failures on passenger service. Table 4-1 lists

---

[1] Preliminary System Specification, The Los Angeles Downtown People Mover, The Community Redevelopment Agency of the City of Los Angeles, October 1978.

[2] St. Paul Downtown People Mover Procurement Bid Package, System Specification, Technical Provisions, Draft, BRW/Kaiser Engineers, October 1978.

[3] Operational Analysis and Failure Management Analysis (Working Paper), Detroit Downtown People Mover Preliminary Engineering Project, GM Transportation Systems Center, September 1979.

[4] Guidelines for Downtown People Mover System Design, Appendix C, Rev. 2, DPM System Performance Specification Guidelines, Office of AGT Applications, UMTA, June 1979.

[5] Alternative Failure Management Strategies for the Los Angeles Downtown People Mover.

TABLE 4-1. ENHANCED FAILURE MANAGEMENT MODELING REQUIREMENTS

Possible Causes of Failure	Failure Effects	Possible Responses to Failure
Type I or Type II Vehicle failure or link control failure	Vehicle stops at the entry to or the exit from a guideway link.	Type I or Type II failure response
Link control failure	Vehicles can neither enter nor leave a guideway link.	Type II failure response
Type I vehicle failure	A vehicle becomes degraded upon entry to or exit from a guideway link and can continue only at reduced speed.	Type I failure response
Type I or Type II failure or link control failure	Vehicle stops at the entry to or exit from a station link.	Type I or Type II failure response
Link control failure	Vehicles can neither enter nor leave a station link.	Type II failure response
Link control failure	Vehicle operation on a station link is permitted only at reduced speed.	Type II failure response
Station or link control failure	Vehicles can neither enter nor leave a station.	Type II failure response

Notes

1. Type I vehicle failure is one which requires that the vehicle be removed from service for repair.
2. Type I failure response is one which involves the removal of a vehicle from service, the transfer of affected passengers, and the dispatch of a replacement vehicle.
3. Type II vehicle failure is one in which the vehicle remains in service after being quickly repaired in the field.
4. Type II failure response is one in which the system is simply restarted under the operation of an effective debunching algorithm.

the general requirements for failure management modeling as they are currently perceived. For each failure effect which is to be modeled in the simulation, the table lists possible causes in very general terms. While it is not proposed that the causes of failure be modeled explicitly, they must be considered by the analyst to specify appropriate failure responses and later to estimate the frequency with which each failure and its associated effect occur during the course of system operation. The causes of failure are grouped into three general categories -- two types of vehicle failures plus control system failures which cause vehicles to stop on the guideway. A Type I vehicle failure is one which requires that the vehicle be removed from service. Type II vehicle failures and control system failures can be repaired in the field and do not require that vehicles be removed from service. The failure effects listed in the table encompass the consequences which are expected to significantly impact passenger delay. All of these failure effects are currently modeled in the DESM and DPMS. Thus, the enhancement of modeling capability which is needed to permit more detailed analysis of failure management alternatives is not in the modeling of failures but rather in the modeling of failure responses. Responses to failures fall into two general categories. A Type I failure response is a rather complicated one which involves the removal of a vehicle from service, the transfer of passengers from a failed vehicle to another revenue service vehicle, and the dispatch of a replacement vehicle. A Type II failure response is one in which the failure is corrected, and the system is simply restarted. In both cases an effective debunching algorithm is required to restore system operation to its former state.

The purpose of this section is to describe alternate failure recovery strategies which are responsive to both the UMTA guidelines and the modeling requirements. The strategies are described in terms of possible responses of system entities (vehicles and passengers) to various types of failure events.

Type II failure responses, ones that do not involve the removal of vehicles from service, can be modeled through the specification of special events for the following system entities:

1. Vehicles which are initially immobilized by the failure
2. Other vehicles
3. Passengers

Vehicles which are at the failure location at the time of failure remain immobilized until failure recovery is initiated. Failure recovery is initiated when the first vehicle affected by the failure begins to move again.[1]

---

[1] In the case of a degradation failure of a station link, vehicles continue in motion across the link, but they operate at reduced velocity. Vehicles entering the link after the time of recovery travel at normal link velocity.

Possible responses of other vehicles whose routes cross the failure location include:

1. Continue in revenue service using an alternate path to bypass the failure location if possible until forced to queue behind the failure.
2. Continue traveling on the route deboarding but not boarding passengers until failure recovery is initiated or until forced to queue behind the failure.
3. Travel to the next station, deboard all passengers, and then continue without stopping at additional stations until forced to queue behind the failed vehicle or until recovery is initiated.
4. Travel to the next station and wait until failure recovery is initiated.

The first response is modeled in the current versions of the simulations; the other three are not currently modeled. The third failure response strategy causes passengers to be deboarded at stations other than their desired destinations. To adequately model this response, passengers who are prematurely deboarded must be reentered into the passenger queue as failure-related transfer passengers. In the special case of a failure in which the entry to an off-line station is blocked, passengers who miss their scheduled stop are deboarded at the next downstream station and are assigned a travel time penalty. This particular response is currently implemented in the software.

The alternative Type II failure responses of vehicles directly affected by failures, other vehicles, and passengers are summarized in Figure 4-1. The various combinations of these responses which are illustrated in the figure represent failure response strategies which may be considered for Type II failures. As indicated above, the two responses listed for directly affected vehicles and the first response listed for other vehicles and passengers are already modeled by the DPMS and DESM.

Type I failure responses, in which failed vehicles are removed from service, consist of a much larger set of possible alternatives none of which are completely modeled in the current versions of the software. Special events for up to five system entities must be considered simultaneously to model many Type I failure response strategies. The following six system entities may be involved in the execution of a failure recovery strategy:

1. The failed vehicle
2. Other vehicles in the system

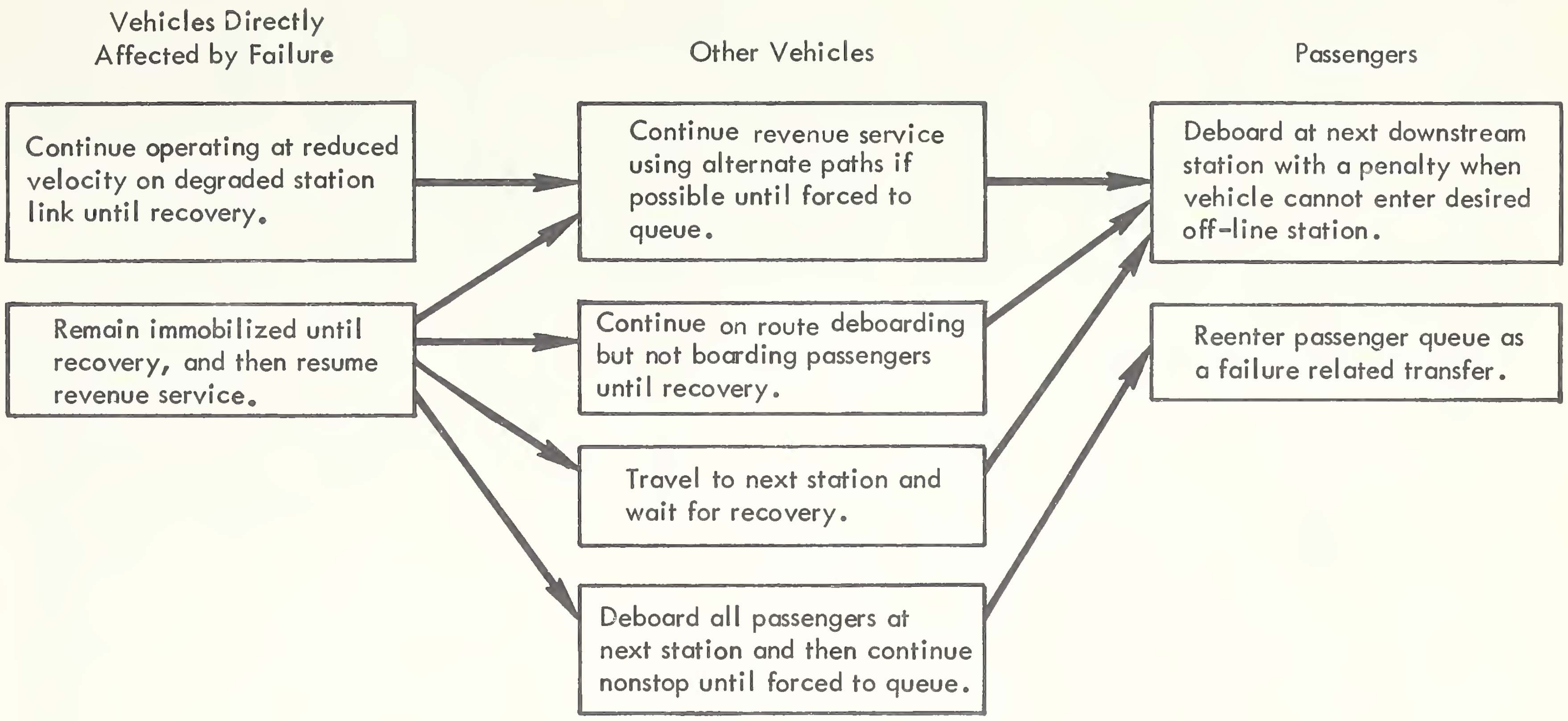

FIGURE 4-1. TYPE II FAILURE RESPONSES

3. The trailing vehicle (the one directly behind the failed vehicle)
4. A special recovery or tow vehicle
5. The spare or replacement vehicle
6. Passengers

The response of the failed vehicle itself is relatively independent of the response of other system entities and includes the following actions:

1. Remains immobilized until recovery is initiated (this time may be zero if the vehicle is merely degraded with respect to operating velocity)

2. Proceeds to the next station at reduced speed

3. Deboards all passengers

4. Proceeds to the nearest maintenance facility or available siding at reduced speed via the minimum path

5. Disappears from the active fleet

The circumstances under which the failed vehicle proceeds to the next station and to maintenance may vary according to the particular strategy. For example, the vehicle may proceed under its own power, be pushed by a trailing vehicle, or be towed by a special service vehicle. The effect, however, remains the same -- the vehicle proceeds at a reduced velocity. One possible variation occurs if the failed vehicle is pushed by the trailing vehicle and the trailing vehicle stops at intermediate stations enroute to maintenance.

Possible responses of other vehicles in the network to the occurrence of a Type I vehicle failure include the following:

1. All vehicles continue in revenue service using an alternate path to bypass the failure location if possible.

2. All vehicles on affected routes continue in revenue service deboarding but not boarding passengers until failure recovery is initiated.

3. All vehicles on affected routes deboard all passengers at the next station and continue without making additional station stops until recovery is initiated or until they are forced to queue behind the failed vehicle.

4. All vehicles enter the next station on their route and wait until failure recovery is initiated.

The first of these possible responses is currently implemented in the simulation software. The last alternative would seriously restrict the failed vehicle recovery strategies that could be considered. In a deployment with on-line stations, use of this strategy would not automatically clear a path from a special tow vehicle to the failed vehicle. If the trailing vehicle must remain in an upstream station, it would not be available to push the failed vehicle. Because of these potential difficulties, the strategy in which all vehicles stop at the next station until recovery initiation is not always a viable alternative.

The trailing vehicle may act as any other vehicle in the system, or it may assume an active role in the recovery operation by pushing the failed vehicle. The following three modes of operation of the trailing vehicle can be considered while it is pushing the failed vehicle:

1. Pushes the failed vehicle at reduced speed to the next station, deboards passengers, pushes the failed vehicle to the maintenance facility or siding, and then resumes revenue service at nominal speed.

2. Pushes the failed vehicle at reduced speed to the maintenance facility or siding, stopping at stations on its route to discharge passengers only (no board events), and then resumes revenue service at nominal speed.

3. Pushes the failed vehicle at reduced speed to the maintenance facility or siding, stopping at stations on its route to board and deboard passengers, and then resumes revenue service at nominal speed.

Only the first alternative was considered in the Los Angeles failure management study. The two passenger responses listed under Type II failure responses also apply to Type I responses. Passengers who are prevented from reaching their desired destination by the blockage of an off-line station entry ramp are deboarded at the next downstream station and are assigned a travel time penalty. When passengers are deboarded prematurely from the failed vehicle or from another vehicle, the passengers will enter the passenger queue as failure-related transfer passengers. The first passenger response is already modeled in the DESM and DPMS while the second must be implemented.

The dispatching of a spare vehicle to replace the one being taken out of service will be handled automatically as a special function of the Fleet Size Management process. Improvements to the existing Fleet Size Management algorithms in the DESM and DPMS are desirable for modeling transitions from one demand period to another in addition to modeling replacement vehicle insertion. Improvements in this area are briefly described in a previous subsection of this plan.

Another vehicle recovery strategy is to dispatch a special guideway utility vehicle to tow the failed vehicle to the next station to deboard passengers and then on to the maintenance facility or siding. The operation of a guideway service vehicle will not be modeled explicitly, but rather as a series of delays which are calculated by the processor and specified by the user. The user must identify the links which define the path of the tow vehicle from its storage location to the point of the failure. The user must also define the coupling delay -- i.e., the time interval between when the tow vehicle arrives and when the failed vehicle begins moving. To implement this response the processor will first fail the exit to all links which merge into the tow vehicle path. The time required for the path of the tow vehicle to become cleared is determined as the time required for the occupancy of all the links along the path of the tow vehicle to become zero. The time required for the tow vehicle to access the failure location is calculated as a degradation factor times the sum of travel times on the links along the tow vehicle's path. After the path has been cleared, the tow vehicle has accessed the failed vehicle, and the coupling delay has elapsed, the failed links associated with merge branches will be recovered, and the failed vehicle will proceed at reduced speed to the nearest downstream station. After deboarding all passengers at the station, the failed vehicle will proceed to the user specified maintenance facility via the minimum path. A replacement vehicle is launched as soon as the failed vehicle begins moving in accordance with the Fleet Size Management process.

The alternative Type I failure responses described above are summarized in Figure 4-2. A complete failure management strategy is represented by a selected response for each affected system entity (failed vehicle, other vehicles, trailing vehicle, tow vehicle, passengers, and replacement vehicle). The various combinations of alternative responses which are illustrated in the figure represent the failure response strategies which may be considered for Type I failures.

Maintenance facilities and sidings can be modeled as the vehicle storage links of selected passenger stations. The feasibility of incorporating code to permit the specification of separate maintenance facilities which have no passenger-handling capability or passenger demand will be investigated.

Cross-overs can be used to minimize the time required to remove a failed vehicle from the guideway by reducing the minimum path from certain network locations to the maintenance facility or nearest siding. Cross-over links can also be specified as a portion of the tow vehicle's path. In most fixed route systems the use of these cross-overs can be reserved for failure responses and fleet size management by specifying station stops on routes which preclude the use of cross-over links.

In an actual system, cross-overs could be used to permit reconfiguration of routes to serve changing demand patterns or as a response to a long term disruption of regular service due to a serious failure. For example, a loop network may be operated as a set of shuttles during certain demand periods or during a protracted failure. In the event of a failure it may not be possible to serve all stations in the network until the failure has been cleared. In order to model the reconfiguration of system operation it would be necessary to modify the code to permit the time dependent modification of routes, transfer characteristics, network configuration, number of stations, and demand. Modifications of this nature would require major changes to the architecture of the DESM and DPMS. The software modifications required to model real time transition from one operating mode to another is beyond the scope of this task. However, the effects of various modes of system operation on system performance can be assessed by comparing the results of separate simulations of reconfigured systems with the simulation results for a reference system.

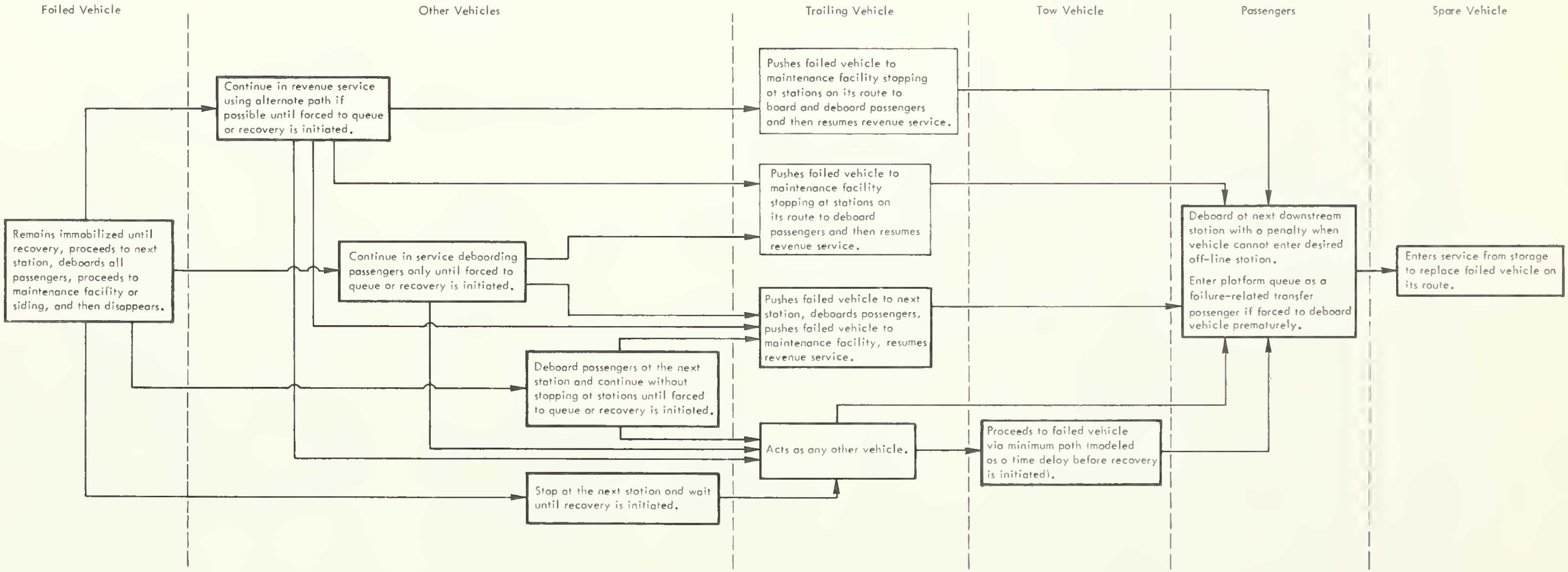

FIGURE 4-2. TYPE I FAILURE RESPONSES AND STRATEGIES

5.0 SOFTWARE MODIFICATION REQUIREMENTS OF ALTERNATIVE FAILURE RESPONSE STRATEGIES

The software modifications required to implement the more detailed failure recovery strategies described above in the DESM/DPMS can be divided into two categories. First, modifications are necessary to implement failure recovery strategies not currently present in the DESM/DPMS, and, second, a method to enable the user to select the appropriate failure response is needed. In the current DESM/DPMS there is a set response for each type of failure with only the time of recovery set by the user, while the more detailed failure recovery strategies will require a greater number of user inputs in order to choose which recovery strategy to follow and to define any other parameters required by the chosen strategy.

FAILED VEHICLE RESPONSE STRATEGIES

Type II Failure

The failed vehicle response of immobilization and subsequent restart on the guideway is modeled by the current software.

Type I Failure

Immobilization of the failed vehicle until recovery is initiated is currently modeled (this time may be zero if the vehicle is merely degraded with respect to operating velocity).

A degraded mode of operation is presently implemented which models vehicle movement at a reduced velocity to the next station, forces all passengers to deboard as if their trips were completed but with a penalty time added, and removes the vehicle from the simulation. Modifications would be required to this mode of operation to model the vehicle continuing at a reduced speed to the maintenance facility before being removed from the simulation and to allow the prematurely deboarded passengers to reenter the platform queues as transfer passengers.

The DESM/DPMS currently directs vehicle travel paths based on the vehicle's NEXTSTATION. In scheduled service, the NEXTSTATION is the next scheduled stop on the route list. In demand responsive service, the NEXTSTATION is the next scheduled station stop on the vehicle's tour. When a vehicle begins degraded operation its NEXTSTATION is reset to the closest station (stop or not) along its route where it will deboard its passengers. This code can remain, but the code which then removes the vehicle from the simulation must be changed. If the current station is the selected maintenance facility, then the vehicle may be removed from service. Otherwise, the vehicle's NEXTSTATION is set to the selected maintenance station; thus initiating travel at a reduced speed to the maintenance facility for removal from the active fleet.

Therefore, the following code is necessary: check if the vehicle has reached the maintenance station, choose the maintenance station as the NEXTSTATION if the current station is not the maintenance station, and avoid boarding any new passengers. The passenger response after premature deboarding is described under Passenger Response Strategies later in this section.

A possible variation exists if the failed vehicle is pushed by a trailing vehicle, and the trailing vehicle continues to make revenue service stops at intermediate stations enroute to the maintenance facility. This variation is fully described under Trailing Vehicle Response Strategies later in this section.

OTHER (UNFAILED) VEHICLES RESPONSE STRATEGIES

The responses of other vehicles after a failure is identical from a software viewpoint for Type I and Type II failures. The currently modeled response of other vehicles to a failure is to continue in revenue service until forced to queue behind the failed vehicle. In addition, at the time of the failure, the minimum path algorithm is reexecuted with an artificially high travel "cost" assigned to the blocked link. This will cause vehicles to travel on alternate paths around the blockage if such alternate paths exist. If not, the vehicles will be forced to queue behind the failed vehicle until recovery. Also at recovery the vehicle paths are restored to the paths which existed prior to the failure.

The alternative response strategies for other vehicles after a failure can be implemented as follows. Code to model a deboard-only mode of operation already exists in the DESM/DPMS to model scheduled service active fleet size modification. This code could be invoked for the after-failure processing of other vehicles, but would require modification to avoid removing these vehicles from the active fleet when they become empty. In addition it would be necessary to assure that this code is also valid for demand responsive service. An additional option would be to make this deboard-only operation valid only for selected routes if in scheduled service, so that routes unaffected by the failure would continue in revenue service.

Code to force vehicles to deboard all passengers at the next station already exists, but the subsequent routing of vehicles along their routes without additional station stops would require recoding for the scheduled service case. Vehicles would continue to be assigned a NEXTSTATION from their route list, but the code to choose whether or not to enter a station would need revision to check a flag denoting whether or not the vehicle was merely circulating because of failure. Also, code to pick the NEXTSTATION if not entering would be needed. Again, this mode might only be applied to vehicles on affected routes. In addition, the effects of this guideway circulation mode on the schedule and subsequent debunching algorithm after recovery need to be analyzed. For demand responsive services, a guideway circulation mode already exists for empty vehicles, but some modifications to the vehicle selection algorithms will be required to reflect the no boarding policy until after recovery.

The strategy of sending all vehicles to the next station on their route to wait until the failure recovery can be modeled reasonably well with the existing DESM/DPMS code by simply failing an appropriate station link in each station. The vehicles would cease operating as they encountered the failed station links and would be prompted to restart operations at station link recovery. This modeling would result in no forced deboarding of passengers; instead, passengers would remain on the vehicles to wait for recovery. More detailed modeling of this response strategy would result in more code modification than could be justified by any increase in useful information. In addition, this response strategy could prove ineffective in the case of on-line stations by blocking the path of tow vehicles to the failed vehicle, as described in the previous section.

TRAILING VEHICLE RESPONSE STRATEGIES

Type II Failure

For Type II failures, the trailing vehicle (the one directly behind the failed vehicle) is treated the same as all other vehicles in the simulation after the failure since there is no need to push the failed vehicle.

Type I Failure

For Type I failures, the trailing vehicle may act as any other vehicle in the simulation, or it may assist in the recovery by pushing the failed vehicle to the maintenance facility. The DESM/DPMS code now treats the trailing vehicle as any other vehicle since the pushing operation is not currently modeled. Software modifications to model the three modes of pushing by the trailing vehicle are described in the following paragraphs.

Modeling of the pushing operation by a trailing vehicle is best accomplished by coupling the trailing vehicle to the failed vehicle and then matching their destinations. This method will enable the modeling of the case where the trailing vehicle is to deboard its passengers at the first station and then push the failed vehicle directly to the maintenance facility. Code would then be required to uncouple the failed and trailing vehicles and to return the trailing vehicle to revenue service. For scheduled service, the trailing vehicle would be routed to the nearest station on its route, while in demand responsive service its destination would be controlled by the empty vehicle algorithm. Thus, modeling of this mode of pushing would use the same code developed to model failed vehicle movement to the maintenance facility except additional code would be required to model the operations after reaching the maintenance facility.

The other two modes of pushing involve stopping at stations along the trailing vehicle's route to deboard passengers from the trailing vehicle, in one case, and to both deboard and board passengers (i.e., full revenue service), in the other case. The implementation of these two pushing modes would require extensive software modifications to accommodate the general case of networks with multiple routes in the DESM/DPMS. The major problem is that the failed and trailing vehicles must be coupled in order to maintain contact with each other during guideway and station link traversal, but retain independent destinations. The failed vehicle has the maintenance facility for its NEXTSTATION while the trailing vehicle's NEXTSTATION is determined by the next stop on its scheduled route or demand responsive tour. It appears that the best way to model the "split destination" of this type of train is to define an additional type of entrainment called "push coupling". In "push coupled" mode, the train's path is determined by the minimum path to the maintenance facility, but at each station diverge, the NEXTSTATION of each vehicle in the train is checked in order to determine whether or not to stop. The code involved in the full revenue service for trailing vehicles would also need to avoid boarding passengers on the failed vehicle. In addition, for all coupling cases, the station links traversed must have sufficient capacity to contain as many vehicles as are included in the coupled train.

Considering the very low likelihood of using such procedures as well as the probable difficulties in implementation, and the questions of safety and quality of vehicle performance involved, we recommend that the latter two modes of failed vehicle pushing which include the "push coupling" entrainment not be implemented. Rather, the only model of trailing vehicle pushing implemented would involve immediate deboard of passengers on both the failed and trailing vehicles. Since the passengers who deboard would subsequently attempt to board the next vehicle passing on their route, the delay would not be much more than before, and possibly less than if they were deflected from their route to the maintenance facility. It would be more beneficial to model alternative methods of handling other vehicles in the simulation which are uninvolved in the recovery effort since the larger number of other vehicles offers more potential to minimize overall passenger delay.

TWO VEHICLE RESPONSE STRATEGIES

The implementation of this failure response strategy involves the calculation of access delays, movement of the failed vehicle to the next station to deboard passengers, and the movement of the failed vehicle to an off-line storage location. Tow vehicle access delays include the time required to clear the path between the failure and the tow vehicle storage location, the time required for the tow vehicle to travel to the failure location, and the time required to couple the tow vehicle to the failed vehicle. Since the tow vehicle is operated under manual control and sometimes travels the wrong way on one-way links, it will not be modeled explicitly as a separate entity. The user will define the path of the tow vehicle from its storage location to the failed vehicle in terms of guideway links. At the specified recovery time, the processor will automatically prevent additional AGT vehicles from entering the path of the tow vehicle by failing the output of links that merge into any links which comprise the specified path. Occupancy on the links that comprise the tow vehicle path will be checked to determine when the path is clear. Tow vehicle travel time will be calculated as the sum of link travel times on the tow vehicle path multiplied by a manual control degradation factor specified by the user. After the path has been cleared and the tow vehicle travel time plus the user specified coupling delay has elapsed, the failed vehicle will start moving toward the next station, and any links which were failed to clear the tow vehicle path will be recovered. A replacement vehicle will also be dispatched at this time. At the next station passengers will be deboarded from the failed vehicle. Any prematurely deboarded passengers will enter the platform queue and will complete their trips on other vehicles. The failed vehicle will proceed to the maintenance facility where it and the tow vehicle will remain. To document the operation of this failure response strategy, the following information will be printed out:

1. The time when the tow vehicle's path becomes clear

2. The time when the tow vehicle arrives at the failure location

3. The time when the failed vehicle begins moving

4. The time when the failed vehicle reaches the maintenance facility or siding.

REPLACEMENT VEHICLE RESPONSE STRATGIES

The initiation of the replacement vehicle will be effected as an active fleet size modification with the improved algorithm described in Section 3.0 on general failure modeling improvements. Replacement vehicle response applies only to Type I failures. When a replacement vehicle is dispatched in response to a Type I failure, the part of the Active Fleet Size modification code which changes the nominal route headway would not be exercised because no net change in the fleet size occurs.

PASSENGER RESPONSE STRATEGIES

It is proposed that the passenger response to failures be modified to allow reboarding of another vehicle (as a transfer trip) for passengers prematurely deboarded because of a failure response strategy. The software modification required is to allow passengers to re-enter the platform queues as transfer trips after prematurely deboarding a degraded vehicle or one otherwise affected by failure. Code currently exists to model passenger transfers between scheduled service routes. It must be verified that this code is valid for these unexpected transfers and for demand responsive service. Until detailed design is completed, it is unclear how much code will need modification to accomplish this change; however, it is known that extensive sections of the code will need to be analyzed to ascertain that the design changes are consistent with the current implementation.

USER RESPONSE SELECTION METHOD

The implementation of alternative failure response strategies will require a more extensive user interface capability than currently available in the DESM/DPMS. The current software distinguishes between Type I and Type II failures but generates a set response to each of these failures. Although the full set of user inputs for the extended failure response strategies will not be determined until detailed design of the software modifications is complete, we anticipate that the following will be chosen by the user in the failure specifications.

*1. Asynchronous event type
    - Failure.
    - Recovery.
    - Degradation.
    - Degradation recovery.

*2. Time of asynchronous event

*3. Failed entity - vehicle, guideway, or station

*4. If guideway link, starting and ending node IDs

*5. If station, station node ID

*6. If station, entire station or station link type

*7. Entire link, link entry, or link exit

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* Currently implemented in DESM/DPMS

*8. If degradation, degradation factor

9. For degraded vehicle removal, station node ID of intended maintenance facility

10. Response of other vehicles in simulation to failure or degradation
    - Continue revenue service.
    - Continue route traversal but deboard only.
    - Deboard all passengers at next station then circulate empty.

    Note: For scheduled service, input this response choice by route.

11. Recovery method
    - Under own power.
    - Push by trailing vehicle.
    - Tow by maintenance vehicle.

12. If tow recovery, link numbers comprising path from tow vehicle storage to failure

13. Service continuation by push vehicle
    - ** Full revenue service.
    - ** Route traversal but deboard only.
    - Deboard all passengers at first station and proceed to maintenance facility.

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* Currently implemented in DESM/DPMS
** Not recommended for implementation

ADDITIONAL MEASURES TO SUPPORT EXTENDED FAILURE MANAGEMENT

It is proposed that new code be added to DESM/DPMS to provide the measures listed below as an aid to the user's understanding of the effectiveness of the selected failure response.

1. Maximum vehicle queue - At the time of failure recovery, the vehicle queue on each guideway or station link is at a maximum. Therefore, code will be written to print the queue occupancy of each guideway link and each station link in the failed station, if applicable. From this information, the user can determine the maximum queue behind the failure if, indeed, it extends beyond one link. (Note: The system architecture maintains separate queues for each link. If the queue of a downstream link is full, the vehicle is forced to queue on the upstream link.)

2. Vehicle removal elapsed time-code will be written to print a message including the time, identity, and location of the failed vehicle being removed from service. The user can then calculate the elapsed time from failure recovery (the failed vehicle begins moving again) to the time of vehicle removal from the active fleet.

It is also desirable from the user's viewpoint to get some feeling for the time required to fully restore service which has been defined in the Los Angeles DPM failure management report as the time to restore equal spacing of vehicles. From an algorithmic viewpoint, this is a very difficult measure to define. However, there is currently available in the DESM/DPMS, a debug flag which will enable the printing of a message defining the entry time of each vehicle at each station. This output defines the station ID, route ID, next station, passenger loading, and several other items at each vehicle entry into each station. These data may be charted by the user to obtain an indication of the time elapsed until full recovery and a feeling for the effectiveness of the selected debunching algorithm in restoring equal spacing on the routes. Alternatively, the values of maximum and minimum interdispatch time for each sampling interval and route can be plotted by the user. When the maximum and minimum values are nearly equal for a route, it can be assumed that equal spacing of vehicles on the route has been achieved.

6.0 RECOMMENDED SOFTWARE MODIFICATIONS

The software modifications we recommend to improve the modeling of failure response strategies in the DESM/DPMS are as follows:

1. Implement additional scheduled service dispatch algorithms to improve debunching control.
2. Improve active fleet size management for the scheduled service case.
3. Implement the ability to include slack time in scheduled service route traversal.
4. Model movement of degraded vehicles to a user-selected maintenance facility rather than to the closest station.
5. Allow user selection of failure response strategies.
6. Model deboard only mode for other vehicles in the network during a failure situation.
7. Model immediate deboard and empty circulation mode for other vehicles in the network during a failure situation.
8. Process prematurely deboarded passengers as transfers rather than completed trips.
9. Model push by the trailing vehicle to a maintenance facility for the failed vehicle.
10. Calculate tow vehicle access time.
11. Produce additional measures of effectiveness of failure response strategies.

It is our plan to develop these software modifications in the sequence listed below in order to enable phased testing and use of the earlier developed algorithms in earlier analyses.

1. Items 1 and 2
2. Items 4 and 8
3. Items 5, 6, and 7
4. Item 3
5. Items 9, 10, and 11

These software modifications, together with the analytical techniques mentioned in Section 5.0, will support the modeling of all the failure response strategies indicated in Figure 4-1 for Type II failures. Nearly all of the failure response strategies indicated in Figure 4-2 for Type I failures are also supported by the DPMS/DESM with the recommended modifications. Only the two trailing push vehicle responses which involve making intermediate stops enroute to the maintenance facility are not to be modeled. In Figure 4-2 these two alternative responses are boxed with a lighter line.

7.0 TASK RESOURCES

Figure 7-1 details the schedule to accomplish the software modifications needed to model the extended DPM failure management strategies. The software modifications implemented under this task will be described in a memo report. Modifications to the appropriate software documents to record these and other software changes will be consolidated under Task 3 - Software Update. Table 7-1 summarizes the estimated resources to be expended in this task.

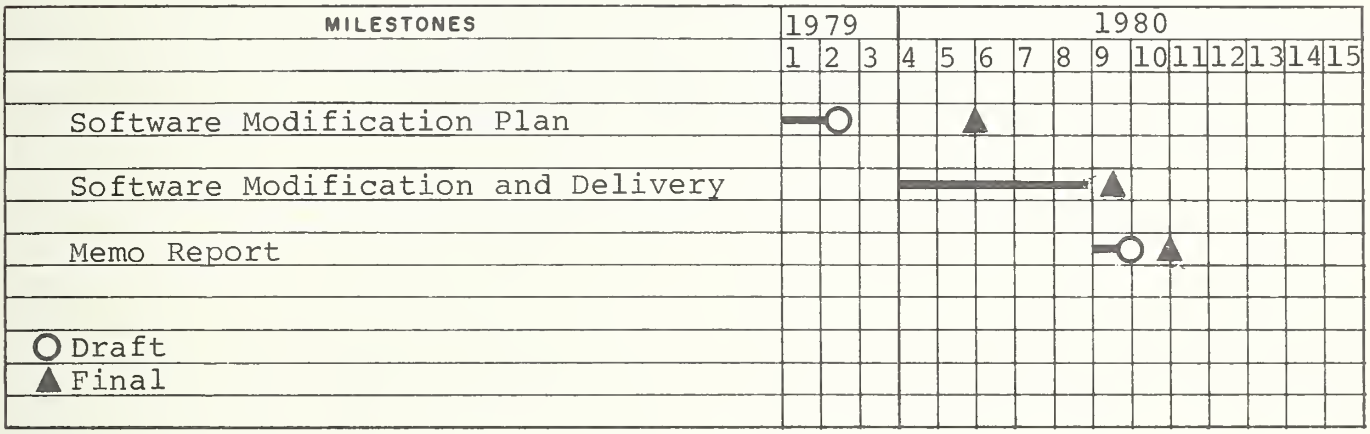

FIGURE 7-1. SCHEDULE, DPM FAILURE MANAGEMENT - TASK 5.0

TABLE 7-1. ESTIMATED RESOURCES, DPM FAILURE MANAGEMENT - TASK 5.0

Total Manpower man-months*	Computer Time hours
9.0	8.7

*One man-month equals 142 applied man-hours.

APPENDIX A

REPORT OF NEW TECHNOLOGY

This report aggregates for the first time in Section 4.0 a variety of failure response strategies and indicates their impact on the unique modelling capabilities embodied in the System Operations Studies software. The specific new software modification requirements are defined for these strategies in Section 5.0.

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