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EXTREME CONDITIONS IMPACT ON RAPID TRANSIT SYSTEMS:

EFFECT ON AUTOMATIC TRAIN CONTROL

SAFETY AND SECURITY STAFF

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16. Abstract

Automatic Train Control (ATC) has gained wide acceptance and is presently used in all aspects of rapid rail operations. Because ATC has limited range of detection, conditions outside those limits might present hazards to transit system operation. With a trend toward less human involvement in the actual operation of rapid rail vehicles, questions have been raised about train safety under ATC failures especially under extreme environmental conditions.

This report examines the impact of extreme environmental conditions and (ATC) failures on rapid rail system safety and makes recommendations to lessen their impact. The environmental conditions covered in the report are: high winds, floods, heavy ice and snow and sub-freezing temperatures as well as lightning. In addition, fires and emergency egress procedures were analyzed in this investigation and recommendations were developed to lessen the consequences of fires and to expedite passenger evacuation procedures.

Overloading, a situation frequently faced by rapid rail transit properties, was also examined to determine its impact on train safety and operation.

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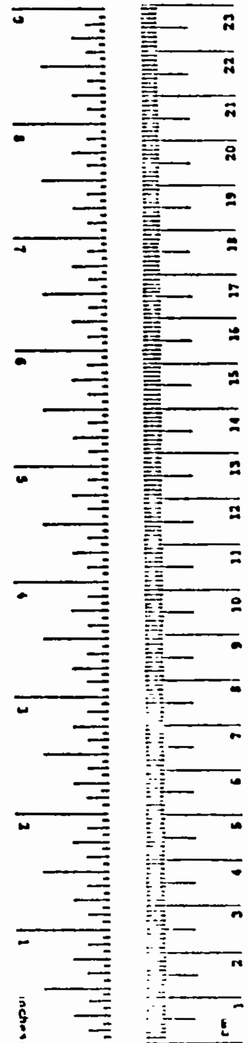
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

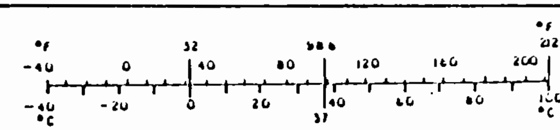
Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	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

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



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



PREFACE

This report was prepared for the Safety and Security staff of the Office of Technical Assistance, Urban Mass Transportation Administration. The report and its contents reflect the views of the authors, not those of the sponsor.

The authors would like to thank all those who have assisted them in the effort to prepare this report. Gratitude is expressed to the staffs of the Washington Metropolitan Transit Authority, and Bay Area Rapid Transit District. In particular we wish to thank Mr. John Flynn of WMATA and Messrs. L. William Breiner and James M. Kestler of BART for their assistance and cooperation.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

EXECUTIVE SUMMARY

Automatic devices are presently widely used in all aspects of rapid rail operation, and the present trend is toward less human involvement in the operation of trains. However, due to the fact that automatic train controls (ATC), under some conditions, such as extreme environmental conditions, ATC failures, and overloading, may fail to perform as expected, questions arise as to train safety under potential failure/emergency conditions. These may occur within the automatic train controls, or may be induced from outside the rapid rail system. In either case, the safety of the train may be seriously impaired. The purpose of this report is to determine if these conditions pose a threat to train safety, and in the event that they do, recommend measures to lessen their impact. In particular this study is focused on the above listed conditions.

ATC may be categorized either by level of automation or by the purpose the different ATC components have. The level of automation involves the following:

- Vehicle/train control
- Station control
- Line/sector supervision
- Network supervision

The classification by purpose involves the following:

- Safety oriented controls
- Operations oriented controls
- Supervision oriented controls
- Support oriented controls

The former classification is concerned with the system performance, and as such, it involves several ATC components. The latter is concerned with the individual roles the different ATC subsystems play in the rapid rail system operation. For this reason, the purpose of automation was selected to analyze the impact of ATC failures, extreme environmental and overloading conditions on train safety. The extreme environmental conditions covered in this report are: high winds, floods, heavy ice and snow and subfreezing temperatures, and lightning.

The severity of ATC failures depend on the particular subsystem involved. Of critical importance is the safety oriented control, since it is charged with checking the performance of the train against set values. These values vary for different sections of the track, in addition, this control is charged with avoiding collision. It does this by checking the occupancy status of the track ahead of the train. Thus its failure may result in collisions and derailments. A subcomponent of the operations oriented controls, the speed regulator, is also critical. Although this unit is checked by the safety oriented control (the overspeed protection) there is a time lag before a speed regulator failure is corrected. Thus, a malfunction in the speed regulator may cause the train to derail or to collide, under special circumstances such as very short headways or short distances to the end of the track.

For ATC to function properly, the performance of the following areas must not be compromised; signal integrity, power integrity, and servo-mechanism and ancillary equipment integrity. Interference with these causes a reduction in the level of ATC performance, and may be detrimental to the safety of the train. Thus, to determine the impact of extreme environmental conditions on train safety, one must determine which and how these three criteria are affected.

Our analysis shows that almost all of these environmental conditions can have a detrimental effect on train safety. The one exception is lightning, which due to the fact that electromagnetic interferences resulting from lightning are not concentrated on any particular frequency, and because the power distribution system is well protected against power surges. These extreme environmental conditions, with the exception of high winds, act on the servomechanisms located in the train and on the track. For instance, floods and heavy ice and snow and subfreezing temperatures, lower the adhesion characteristics of the track, with floods having a lesser effect. Thus, because a moving train will require longer distances to stop under these conditions than when operating on dry tracks, these may cause a train to collide with a standing train. Heavy ice and snow and subfreezing temperatures can also interfere with the proper functioning of the track switches. This is the result of icy material which is deposited or formed in the switch path, impeding the proper alignment of the switch with the track. This condition may result in the train derailing as it changes tracks. High winds do not interfere with the ATC itself, but it can impose lateral loads on the train body. However, in order to have an impact, the winds must be extremely high, in the order of 80 miles per hour or more. Lesser wind speeds, however, can deposit debris on the track, these, as the train passes over, may be thrown against the undercarriage causing damage to the electric equipment and subsequent possible electrical fires.

Undercarriage fires, however, are not the only fire threat to train safety, as fires can also originate within the train. Undercarriage fires become a serious threat if they are able to breach the floor or the wall/floor junction. If this occurs, the fire may cause the interior wall liners and seats to ignite and may possibly involve other cars in the train. Interior fires are more dangerous because of the availability of flammable material inside the train.

Although extreme environmental and overloading conditions, ATC failures and fires, may not result in disastrous consequences, it may be necessary for patron safety considerations, to evacuate the passengers at locations other than stations. This is accomplished in either of two ways: 1) by requiring that the emergency egress procedures take place only after fire, police and the property personnel are at the incident area, or 2) by allowing some degree of passenger involvement. In the latter case, the passengers may see themselves out to a safer area in case it becomes absolutely necessary to leave the train on a short notice. The former method is practiced by WMATA, while the latter is prefered by BART.

To determine the impact of overloading on train safety a survey of several transit authorities was performed. These were: BART, WMATA, CTA, NYCTA and PATCO. From the survey it was ascertained that overloading does not pose a safety hazard. It is an operational problem only when the train doors can not close, and this only for those properties with trains programmed to depart after the doors are closed (Vehicle/train control). For train operation under manual control this condition is no problem at all.

Our analysis indicates that almost all the conditions studied in this report lead to collisions or derailments, and in the case of high winds, to fires. In order to lessen their impact, the following recommendations are proposed:

For High Wind Conditions:

- Trains should be operated under semiautomatic control, and at speed that would permit the safe negotiating of horizontal curves, until the condition has passed. At slower speeds, there is less chance that debris deposited by the wind may damage the electrical equipment in the undercarriage.

- Train operator should be responsible for deciding if operational speed is safe. This in light of the fact that since the operator is at the scene, he or she can decide, based on visual observation, if the wind is too strong.

For Flood Condition

- Check for flooding should be performed automatically by a system of pumps, and the system should notify central control and the station having control over the area affected.

- Traffic through the area should be stopped until all repairs have been made.

- Third rail power should be removed as soon as practicable.

For Heavy Ice and Snow and Subfreezing Temperatures

- Track switches should be kept operational by frequent manual activation.

- Track switches should be equipped with heaters.

- Visual signals associated with their operation should be operational, and cruising speeds lowered to insure that the train will be able to stop in case of switch malfunction.

- Trains should be operated over exposed sections of the track to keep it operational.

For Collisions

- In sections of the track with short line-of-sight installation of one or more police type lights at area entrance. These should be activated automatically as the train enters, and deactivated as the train leaves the area.

- Installation of police type lights on highly visible part of the train. The operation of this device should be manual from the cab.

For Derailments

- Switches should be inspected daily for failures in the power system, visual signals, automatic controls, and for mechanical integrity.

For Fires

- Cooperation agreement between the different fire departments where the transit property operates, so that they know who is responsible for what areas.

- Procedure for the operation control center, indicating clearly, which fire department is to be contacted in case of fire.

- Floor areas susceptible to undercarriage fires should be protected with fire resistant coatings, or the floor made of fire resistant materials.

- Vehicles should be cleaned frequently to avoid accumulation of flammable materials.

- Patrons should be discouraged from leaving newspapers or other paper materials when they leave the train.

- Seats and liners should be made of fire resistant material. Carpets should be made of fire resistant materials or treated with fire retardants.

For Emergency Egress

- An emergency egress similar to the one in effect at BART is recommended.

1.0 BACKGROUND AND INTRODUCTION

Although the first control device introduced to transit systems was the motor controller in the 1900's, the true impact of automation started with the cab signal controls (a form of the block control systems) in the 1930's. This impact continued to grow in the following decades, from areas of vehicle separation to vehicle performance, line and sector control to network management. Today, in the 80's, innovative control systems such as variable block controls, vehicle borne performance controls, as well as a multitude of sophisticated monitoring devices which can be designed to the specific requirement of any transit system and programmed with desired react capability, have extended the impact of automation to almost all the facets of train operation.

However, not suprisingly, operators on vehicles and in the central are still universally required. This is because of certain human functions which although they can not be totally specified are known to be not replaceable by automatic devices. It proved to be difficult, from previous attempts to precisely define the universe of functions required of transit operators, to divide them into automatable and non-automatable terms. This is largely due to the fact that human functions and reactions can not be all classified into neatly quantifiable blocks as devices could.

Automation features have been widely applied and accepted in rapid transit systems, both foreign and domestic, with excellent results in train performance and train safety. However, the use of automated features in existing transit systems raises questions as to the reliability of these devices during abnormal conditions. These questions are being more often asked when a new transit system is being introduced and its degree of automation is to be selected. This study attempts to answer some of these questions by analyzing the implications of automation on train safety during extreme abnormal conditions*.

To answer these questions, this study examines the role of the various components involved in the operation of rapid rail systems and assesses the impacts of extreme conditions on their operation. Specifically, since Automatic Train Control (ATC) involves the use of servo-mechanism to perform the duties traditionally performed by human operators, it may be classified either from an organizational or level of automation point of view, that is, how rapid rail train operations control is exercised by the ATC; or from a mission oriented or purpose point of view, that is, what role the various ATC components play in the different aspects of rapid rail train operation. However, in order to assess the impact of extreme conditions on the ATC, it is necessary to understand how its different components control the different aspects of train operation. This is done in section 2.0 of this report.

Although these devices have been incorporated into U.S. and foreign operating transit properties, for some of these properties, automation has not been implemented system wide. The trend, however, appears to be towards a greater reliance on automation. This is more evident in the newer transit properties, where almost all the human functions have been replaced. Two of these properties (Bay Area Rapid Transit and Washington Metropolitan Transit Authority), have been in service for several years. Since they represent the most automated systems presently in use in the U.S., their operating experience is taken as the point of reference from which to learn how automated rapid rail systems cope with extreme conditions. A brief

* Abnormality is defined here as externally induced or resulting from the environment or internally induced or resulting from within the automatic controls.

description of select U.S. and foreign transit properties is given in section 3.0 of this report.

The use of servomechanisms to perform certain duties result in improvements in all aspects of train control. This is due to the fact that machines are more reliable than their human counterparts especially in performing repetitive functions. However, ATC is vulnerable to conditions it has not been programmed to cope with. This study addresses these conditions, assesses their impact on train safety, and for those found to be detrimental to train safety, proposes countermeasures to minimize their effect.

The environmental conditions considered in this report are: high winds; floods; heavy ice and snow, and sub-freezing temperatures; and lightning. Other conditions such as rain, sleet, and hail are not examined because their effect is similar to conditions to be discussed. These extreme environmental conditions, as well as internally induced abnormalities and overloading conditions are discussed in section 4.0 of this report. This section also includes recommendations to lessen the impact of these conditions as well as recommendations to minimize the incidence of collisions and derailments.

Needless to say, since these servomechanisms control the operation of the trains, their failure have severe implications to the safety of the consist. These, however, are not the only circumstances that threaten the safety of the train. One incident of potentially grave consequences is the presence of fires in the consist. Fires may start in the inside of the train, in which case they generally are the result of acts of vandalism; or in the undercarriage of the train, in which case they are generaly the result of short circuits or poor power dissipation in the vehicle electric equipment and brakes. In either case, the safety of the train, is seriously affected. The problem is compounded if flammable material used in train interiors, and/or poor fire resistant floor materials are used. Section 5.0 deals with these issues, and proposes recommendations to lessen the incidence and severity of fires.

Finally, since in the event of ATC failure or fires, it is the safety of the passangers that is at stake, an analysis of present methods of passanger emergency egress is performed. From this analysis, procedures to insure the safety of the property partrons are recommended. These topics are treated in chapter 6.0 of this report.

2.0 AUTOMATIC TRAIN CONTROL CLASSIFICATION

Train control is the process by which the movement of rapid rail transit vehicles is regulated and supervised to assure safety and efficient operation. When automated, the process is performed by machines rather than human operators. Automatic train control may be classified according to the level or purpose of automation. In this section, the different components that make up the automatic train controls are examined according to this classification. In addition, this examination will: 1) determine which of the two schemes of ATC classification offers a more advantageous point of view in determining the impact of extreme conditions on train safety, and 2) pinpoint the weaknesses found in automation that would make the system vulnerable to extreme conditions.

2.1 Levels of Automation

To consider automatic train control in its general scope, four levels of automatic control hierarchy exist. From a bottom up point of view, these are:

- Vehicle/Train control;
- Station control;
- Line/sector control; and
- Network/central control.

A specific system may not have all these four levels on its control system necessarily divided in this manner. This hierarchy provides a logical framework to examine the automatic control designs transversing different types of systems. These controls are described below.

2.1.1 Vehicle/Train Control

The purpose of the vehicle/train control is to move the vehicle/train and stop it at stations to accept and discharge passengers. It involves the functions of: speed regulation, station stopping, door control and train starting.

The purpose of speed regulation is to regulate the train speed, within some specified limit, so that it makes the run according to schedule. It includes control of acceleration, slip/slide control, and flare-out. Slip refers to the slipping of the wheels during the application of power; slide is concerned with the wheels sliding over the rail when brakes are applied. Flare out is the gradual easing-off of the brakes to achieve a smooth deceleration.

The purpose of station stopping is to bring the train to a complete stop, within some specified area in a station, and to keep it there until it is over-ruled by the train starting function.

The purpose of the door control and train starting function is to open the doors when the train comes to a halt at a station, to allow passengers to board or alight the train, and to close the doors when the train is ready to depart. This function also starts the train on its way after the doors are closed.

2.1.2 Station Control

Station control comprises two different major functions: one relates to the train, and the other relates to the passenger.

Train related functions are made up of two sub-functions: dispatch function and command functions. The dispatch function monitors the switch area the train must pass, and makes the necessary switch and route assignments. The command function instructs the train control unit of any speed changes that need to be made to keep up with the schedule. It also monitors the train functioning while it is at a station.

Passenger related functions inform the public at the station, through public address systems or visual aides, of the destinations and departures of the trains.

2.1.3 Line/Sector Control

The purpose of the line sector control is to monitor both the traffic and the system status, to include the sector's power distribution system. It provides the appropriate instructions to direct the operation of the trains in order to maintain the intended traffic patterns and minimize the effects of train delays on the operating schedule.

2.1.4 Network/Central Control

The purpose of the network/central control is to exercise control over the entire system. It involves operational and supervisory functions. The operational functions involve dynamic control of the system's operation and response to emergencies. The dynamic control function entails changing of the current arrival/departure schedule by altering the dwell-time at stations, or by adjusting the train speed/performance while in movement. The response to emergencies function consist of a number of specific sequence of instructions which are triggered by unusual circumstances, and which are of immediate danger to the safety of the trains.

The purpose of the supervisory function is to assure smooth operation of the system at all times. This function comprises the following:

- Selection of pre-programmed schedules and routes
- Assignment of trains on routes
- Introducing (or extracting) trains into (out of) service
- Start-up operations (gradually procedured)
- Supervise sector and station routines
- Coordination/Supervision with yards
- Supervision over power distribution
- Supervision over total network/vehicle activities
- Communication/monitor with total system personnel
- Response to emergency assisted by pre-programs.

2.2 Purpose of Automatic Train Controls

From a mission oriented point of view, the components of the automatic train control (ATC) may be divided into several categories according to their main purpose. These are: safety, operation, supervision, and support.

2.2.1 Safety Oriented Controls

The purpose of the safety oriented controls is the protection of the equipment and more importantly, the protection of human lives. In order to accomplish a high level of protection, three distinct areas of train operation are monitored and controlled. These are train separation, overspeed protection, and route interlocking.

The purpose of the train separation function is to maintain a safe distance between following trains so that there is no danger of colliding with each other.

The purpose of the overspeed protection function is to insure that the train does not operate at speeds greater than the commanded speed. These commanded speeds vary according to the track characteristics and conditions, i.e., horizontal profile (targets and curves), vertical profile (lines and curves), track interlocking areas, etc.

The purpose of the route interlocking control is to assure that the train moves along a selected route free from the danger of collision or derailment. This is accomplished by preventing conflicting moves along lines or through switches. The interlocking system consists of a series of signals and signal appliances arranged in such a way that their functioning is sequential, in accordance to some predetermined rule. That is, one safe signal triggers another safe signal. In the event of a component malfunction, the sequence of events is stopped and permission to enter and cross the interlock area is not granted.

2.2.2 Operations Oriented Controls

The purpose of the operations oriented control is to keep the train running according to the established schedule, provide a smooth ride and insure that station stops and departures are uneventful. The operations control comprises the functions of speed regulation, platform line-up, door control and starting. These have been discussed under Vehicle/Train Control (section 2.1.1).

2.2.3 Supervision Oriented Controls

The purpose of the supervision oriented controls is the overall management and monitoring of the system. The different functions that comprise the supervision oriented control are discussed under Network/Central Control (section 2.1.4).

2.2.4 Support Oriented Controls

The purpose of the support oriented controls is to schedule preventive maintenance, and update maintenance records.

2.3 Advantages and Limitations of ATC

Many of the functions performed by human operators have been replaced by automatic control devices, so that now these devices are found at all levels of train control. The advantages and limitations of automated and manual controls are discussed in the following sections. Table 2-1 presents a brief survey of the functions, by level of train control, which have been automated, and those which remain the domain of the operator. Table 2-2 shows the different functions, in relation to their mission, that have been automated, the gains by using automation, and the limitations of these devices.

2.3.1 Advantages

The advantage in choosing ATC over manual control lies in the ability of the former to perform reliably in the various duties required to operate, protect, and supervise the train, under a wide range of conditions. By contrast, human operators are not as reliable, as they may and do, misinterpret instructions and/or conditions about the train. In discharging their duties, both human operators and machines go about it the same way: by monitoring the performance of the train against some set standard.

The superiority of the machine manifests itself in four ways: 1) it is faster to react to abnormal conditions or new instructions, 2) it is more accurate in its response, 3) it is tireless, and 4) it is oblivious to anything that is not related to the events it is programed to react to. By contrast the human operator is slow and not so accurate in his reaction towards abnormal situations. In order to react, the operator must first be aware of abnormal conditions, the information must be assessed to determine the level of response, and finally the response must be implemented. Although machines go through the same cycle, they go through the cycle much faster

Table 2-1

SURVEY OF MANUAL AND AUTOMATED CONTROL FUNCTIONS

I Network Supervision (Central)		II Line Supervision (Sector)		III Station Controls		IV Train/Vehicle Controls	
(IA) Operator	(IB) Supervisor	(IIA) Operator	(IIB) Supervisor	(IIIA) Operator	(IIIB) Attendent	(IVA) Operator	(IVB) Attendent
• Up grade (or retard) schedules via dwell-times • Adjust trains speeds/performance on route • Response to emergency on spot (in addition to column IB)	• Selection of pre-programmed schedules & routings • Assignment of trains on routes • Introduce (or extract) trains into (out of) service • Start-up operations (gradually procedured) • Supervisory sector & station routines • Coordination/supervision with yards • Supervision over power distribution • Supervision over totally network/vehicle activities • Communication/monitor with total system personnel • Response to emergency assisted by pre-programs	Traffic adjust on line (or sector) (in addition to column IIB)	Section power distribution controls	Station area dispatch (switchings) station area command (speeds) (in addition to column IIIB)	Passenger Related • monitoring • information • facility Central Related • communication • visual & audio monitoring	• Speed • Stops • Traction (in additon to column IVB)	• Doors/passenger • Communication to passenger • Deadman feature • Basic failure monitoring • Visual monitor • Audio monitor

Category I, II, III, and IV: levels of automation
Columns (A). maximum human involvement
Columns (B): minimum human involvement and maximum automation

Table 2-2

GAINS AND LIMITATIONS FROM IMPLEMENTING ATC

TOPICS	DEVICES	HUMAN FUNCTION REPLACED	GAIN BY USING AUTOMATION	LIMITATIONS
1. VEHICLE SEPARATIONS	BLOCK CONTROL	DRIVER FORWARD TRAIN MONITORING & SPEED CONTROL (BRAKING)	NO ERROR IN FORWARD TRAIN MONITORING AND BRAKING	OTHER OBSTACLES FORWARD ON TRACK
2. SPEED PERFORMANCE (TIME/SPACE)	SPEED CONTROL (SPEED-SPACE PROFILE)	DRIVER SPEED MONITORING AND ACCELERATION/ DECELERATION	----------	PERFORMANCE FLEXI-BILITY LOST (CONTINUITY SPECTRUM)
3. OVERSPEED	SPEED LIMITOR	DRIVER SPEED MONITORING AND BRAKING	NO ERROR IN OVERSPEED LIMITING	
4. PLATFORM LINE-UP	MAGNETIC INDUCED LOOPS	DRIVER SIDEWAY MONITORING AND BRAKING	NO ERROR IN VEHICLE/ PLATFORM LINEUP	VISUAL DETECTION OF PLATFORM/TRACK OBSTACLE
5. DOOR CONTROLS	STATION-WAYSIDE-SIGNAL / ON BOARD SERVOMECHANISM	DRIVER GIVING BOOK COMMANDS	NO ERROR IN WHERE DOORS OPEN/CLOSE CONTROLLED DWELL TIME ACCURATE	VISUAL DETECTION OF PASSENGER AT DOOR
6. TRACK ASSIGNMENT/ STATION	CENTRAL COMMAND SWITCHING	STATION OPERATION, RECOGNIZING WHICH TRAIN, MONITORING, MANAGING & APPLICATION SWITCHING	NO ERROR IN NO. TRAIN/NO. TRACK ASSIGNMENTS	NO FLEXIBILITY
7. HEADWAY CONTROL	REMOTE COMMAND OF TIME/SPACE CONTROLLER (VIA PROFILE)	SECTOR OPERATION: MONITOR SPEED & COMMAND. DRIVER: RESPONSE & ADJUST	CENTRAL OVERALL ADJUST AMONG TRAINS TO ACHIEVE RELATIVE HEADWAY. NO UNRELIABLE HUMAN EXECUTION ON BOARD.	LESS FLEXIBILITY
8. INTERLOCKING (# TRAIN/# SWITCH)	TRAIN I.D. ACTIVITIES PRE-PROGRAMED SWITCHES	SECTOR OPERATION: IDENTIFY TRAIN, MONITOR, ACTIVATE SWITCHES	NO ERROR IN NO. SWITCH ASSIGNMENT	-------------
9. ROUTES ASSIGNMENT	MICRO PROCESSOR (AT CENTRAL) PRE-PROGRAMMED ROUTE - SOFTWARE WITH STATUS OF ALL TRAINS	HUMAN CHECKING & SELECTION OF TRAIN CONSIST FOR ROUTES	ESSENTIAL INFORMATION ASSISTANCE COMPUTED AIDED DECISIONS EXTEND COVERAGE, SHORTEN ASSIGNMENT TIMES, REDUCE ERRORS.	FINAL DECISIONS BY SUPERVISOR -----------

Table 2-2 Continued

GAINS AND LIMITATIONS FROM IMPLEMENTING ATC

TOPICS	DEVICES	HUMAN FUNCTION REPLACED	GAIN BY USING AUTOMATION	LIMITATIONS
10. SCHEDULING	MICRO PROCESSOR PRE-PROGRAMMED SOFTWARE WITH SCHEDULE FOR ALL PERIODS OF DAY.	LABORS ON SELECTING & MAKING OF SCHEDULES	FACILITATE SELECTION OF SCHEDULES. FACILITATE MODIFICATION OF SCHEDULES, REDUCE ERRORS.	FINAL DECISIONS BY SUPERVISOR
11. FLEET MANAGEMENT	DATA COMMUNICATION WAYSIDE/VEHICLE CONTROLLERS STATION & SECTOR COMMANDD & CONTROL. CENTRALIZED DISPLAYS.	TO COMBINE INDIVIDUAL VEHICLE PERFORMANCE INFORMATION FOR CENTRALIZE DECISION USE.	CENTRALIZE & FACILITATE SECTOR BY SECTOR, SYSTEM WIDE MONITORING, CONTROLS AND COORDINATION INFORMATION/COMMUNICATION WITH VEHICLES.	FINAL DECISIONS BY SUPERVISOR
12. SYSTEM MANAGEMENT	VOICE COMMUNICATION COMPUTER STATUS PRINTOUT, TV MONITORING	VARIOUS STATUS ANCILLARY SYSTEMS INFORMATION GATHERING	INSTANT COORDINATION WITH YARD, MAINTENANCE CREW, STATION & VEHICLE OPERATIONS, ESSENTIAL INFORMATION/COMMUNICATION ASSISTANCE VEHICLE SYSTEM	FINAL DECISIONS BY SUPERVISOR
13. POWER DISTRIBUTION	COMPUTER PRINTOUTS CENTRALIZED STATUS	DISTRIBUTED POWER INFORMATION GATHERING	STATUS OF POWER SYSTEM MONITORING & CONTROL	FINAL DECISIONS BY SUPERVISOR

than human operators. In addition, the level of response has been predetermined, a given condition calls for a given response and no other, thus, machines do not hesitate, they merely implement the response which since it has been predetermined for a particular condition will be performed in the same way every time it is called. The biggest advantage that machines enjoy over human operators who are subject to physical and/or emotional stresses, is that machines are impervious to such distractions since they can only understand and react to the events they have been programmed for.

The superiority of automatic train controls can be appreciated by comparing the accident record in operations in which the ATC is in full command as it is in main-line service, and those in which the level of ATC control has been reduced in favor of manual control as it is in yard operations. For instance, in the yards, the train separation automatic control function is not operational. In some yards, route interlocking is manually performed by a flagman. Table 2-3 shows the number of collisions, derailments, and the major cause for accidents that occurred in main-line service and in the yards during 1980. From the Table, it can be seen that more accidents happened in the yards than in main-line service. In addition, the most frequent cited cause of all these accidents is human factors. The section listing major causes also includes errors that resulted in fires. However, it is not possible to determine which of the four listed causes is responsible for the fires.

2.3.2 Limitations

Although automation is superior to human operators in several respects, and has taken over many areas of train control, it is unreliable under conditions the system was not designed for. For instance, the train protection system will maintain the train's speed below certain critical limits such

Table 2-3

COLLISION, DERAILMENTS AND MAIN CAUSES FOR 11 MAJOR

RAPID RAIL TRANSIT SYSTEMS IN THE U.S. DURING 1980

	Collisions	Derailments
Main-Line	5	6
Yard	13	14
	18	20

Main Causes of Train Accidents*	Frequency
1. Human Factors - Rules and Instructions	17
2. Human Factors - Speed	1
3. Mech/Elec-Locomotives	2
4. Track - Frogs and Switches	3
	23

Source: Rail Transit Safety, U.S. DOT, September 1981

* Some of these resulted in three fires

as when the train is entering a horizontal curve. As long as the environmental conditions are what the system was designed for, the system can be expected to perform as intended.

However, if these conditions are changed, the system may not be able to compensate for these variations. For example, a train entering a section of track which is flooded will continue to operate at the cruising speed for that area, without regard to the fact that stopping distances are longer on wet than in dry tracks. Unfortunately, it is in these circumstances, when the automatic train protection system becomes inadequate and is set aside in favor of the human operator, that accidents often happen.

2.4 Conclusions

Of the classification schemes, levels of automation and purpose of automation, the former is oriented toward system management, as such it is concerned with train performance, and each level involves several ATC functions. Thus, the level of automation scheme is more suitable for studying how the different ATC components interact in running a train system. The latter classification is not as complex as it points out the specific duties of each of the components of the ATC. And knowing what exactly they do, it is possible to establish the possible consequences of their failure. For this reason, this classification will be used in determining the impact of abnormal conditions on train safety. This analysis is conducted in section 4.0 of this report.

3.0 STATUS OF AUTOMATION IN TRANSIT SYSTEMS

To ascertain the trends in train operation, several rapid rail systems, operating in the U.S. and foreign countries will be reviewed. Some of these systems have been in operation for many years, others are relatively new. Thus this chapter will provide a clear view of present day philosophy concerning train control, and will facilitate the selection of a set of transit systems from which to learn about how they cope with extreme conditions.

3.1 U.S. Operating Systems

In the United States there are a broad spectrum of transit systems representing various levels of network size, sophistication and system age. Three systems, Chicago Transit Authority (CTA), New Jersey Port Authority Transit Corporation (PATCO), and Bay Area Rapid Transit (BART), were selected as representing different levels of automation and system age. The following sections briefly describe these systems technology and operation as representative of existing U.S. systems.

3.1.1 Chicago Transit Authority (CTA)

The rail portion of the CTA system consists of seven lines, six of which serve the downtown area. Through the past decade, CTA's train control system has been upgraded, going from almost completly manual to some degree of automation. Presently, except for train separation and speed regulation which are functions performed by wayside or cab signals, the train is manually controlled by the operator. This represents the fundamental automation requirements of a transit system.

3.1.2 New Jersey Port Authority Transit Corporation (PATCO)

The PATCO system also known as the Lindenwold High Speed Line, comprises a single line serving suburban communities in southern New Jersey and the city of Philadelphia.

The Lindenwold train control system is a mixture of manual and automatic controls in which all safety oriented functions are automated. This is achieved by a combination of carborn, wayside and track equipment. Train operation is also automatic, however, not at the level of the safety oriented functions. An on-board operator controls door opening and closing. He also controls train departure by pressing a start button on the cab console. Upon depressing the start button, provided the doors are closed, a sequence of events is initiated automatically, the train accelerates, proceeds to the next station, decelerates and brakes to a stop.

Although the Lindenwold system, under normal conditions, is operated automatically, in some circumstances, it is under manual control. This is done, usually in bad weather conditions. In addition, in order to maintain operator proficiency, operators are required to run the train, manually for an entire trip once a day.

Contrasting the train operation, which is normally automatic, train supervision is largely manual. This function is accomplished by dispatchers at a central station control board who supervise train movements, order schedule adjustments, and monitor the overall system performance. Routing is automatic but can be overridden by central control.

3.1.3 Bay Area Rapid Transit (BART)

The BART system consists of 71 miles of double track routes serving the San Francisco Bay area and suburban communities for both San Francisco and Oakland. All of BART's control systems, train protection, operation and supervision, are highly automated.

The automated equipment that supervises the operations of the trains is partly on board the train, partly at waysides, and partly in a computer complex. The train protection and operation functions are performed by wayside, station and carborne equipment. Dispatching and schedule maintenance and adjustments are carried out by the central computer, and by wayside and carborne equipment.

Two PRODAC 250 computers form the nerve center of BART's central control, one of the '250' computers serves as the central control computer and the other serves as an on-line backup. The functions of the computers include train identification, dispatching, route selection, performance control and monitoring, and schedule adjustment. The BART control logic is as follows:

- An "optimal" schedule is pre-selected for the particular time of the day. Then trains are chosen to run on various routes that are formed by combinations of interlocks.

- Each train's performance is monitored by Central Control, and its performance is compared to the theoretical performance--i.e., where it should be or when it will reach the next station. If delays occur, Central will send a six-bit message to the next station, commanding an increase in vehicle speed on the section of the track from this station on. However, if these adjustments can not maintain the train's schedule, Central will send commands via stations to all trains on the same route to slow down an appropriate amount in order to maintain the appropriate train separation and absorb the delay, thus preventing delay propagation. In case this scheme fails too, a new schedule must be selected from the simulation computer.

Originally designed to control 105 trains at 90-second intervals during peak hours, the system, due to operational delays resulting from safety considerations, and high equipment failure, operates about 40 trains at 3 1/2 minute intervals. Besides the speed adjustment arrangement mentioned above, Central can also modify the performance through station dwell time, as well as station skippings.

Central Control and the computers are located at the Headquarters of BART on top of the Lake Merritt Station. There are three display boards for displaying status of routes, power distribution, and support facilities. These display boards are driven by the central computer. Alarms are communicated by a flashing symbol on the display board, and by a Cathode Ray Tube (CRT) display on the console and a teletype for logging purposes. These alarms represent such things as route requests, trains ready for dispatching, etc.

The supervisor has two sets of keyboards and a telephone on the control console. He uses one set of keyboards and the CRT to communicate with computers in obtaining the necessary information for his decisions. Once a decision is made, he sends the commands to the hardware system by the other set of keyboards. The supervisor thus serves as an interface of the automatic control system. Most of the routine operations are completed without supervisor intervention.

3.1.4 Comments on U. S. Operating Systems

In the U.S. the experience with operating transit systems has been quite lengthy. During the history of operation each new generation of transit system sought to integrate advances in technology into their system design. More recently, the recognition that automation is an important contributor to system safety and improved operations has resulted in the fact that contemporary systems now are designed with automated control as the prime operating and safety system, such as in the Washington, D.C., Atlanta, Baltimore and Miami systems.

Today the older sysems of the United States are begining to investigate automated controls to be retrofitted on certain segments of their networks as they renew these parts of their systems. This trend will become more prevelant as the operating properties seek to modernize and upgrade their systems.

3.2 Deployed Automated Systems

In recent years as experience with automation and new technologies developed, fully automated systems, that is, systems in which the human operator has been totally replaced by automated devices, have gone from the experimental stage with limited application to deployment as urban transportation systems. The three systems discussed in the following sections represent different operating and attendant philosophy to achieve totally automated operations.

3.2.1 Osaka South Port New Transportation System (New Tram) - Japan

The New Tram system is a double track, single lane system about four miles long. The system connects two port islands with the commuter/subway sytem which serves the greater Osaka area.

The train control system in the New Tram is fully automated but an attendant is present at all times for emergency management and to assist in door operation. The components of the train control system are related to safety, operations, and supervision.

The safety oriented system consists of a five block degradation scheme via vehicle borne transmitter mutually coupled with wayside loop. The operations oriented system consists of the Sector Control Unit (SCU) and Terminal Control Unit (TCU). The TCU is the central control. Trains are handled from sector to sector with speed codes given by SCU before departure for the next station. The supervisory oriented system consists of the TCU which performs fleet management. It has double redundancy and triple redundancy subsystems to perform pre-programed functions while interfacing with the central control supervisor.

3.2.2 Kobe Port Island New Transportation System (Portliner) - Japan

The Kobe Portliner system services the city of Kobe and Port Island, a man made island. It consists of a two lane track section connecting the two sites, and a one lane track section in the form of a loop. The latter connects various business centers in the island. Like the New Tram it is about 4 miles long, however, it differs from it in that all its major components, that is, the command, control, and communications system as well as the vehicles are of Japanese manufacture.

The train control system in the Kobe Portliner is also fully automated, but an attendant is present at all times to assist in door operation. Like the New Tram system, train control components consist of safety, operation and supervisory oriented controls.

The safety subsystem consists of fixed block control, check-in/check-out block system via vehicle born transmitter with redundant controls to insure safe operation at all times. The operation subsystem consist of on-board speed controller which is activated by speed codes. It also includes routing and door controls. The Central Control subsystem is composed of supervision and operations oriented functions for vehicle control. Fleet management is based on preset schedules, and dwell time adjustments.

3.2.3 The VAL System - France

The Val system is a double lane exclusive guideway system, the first section of which was scheduled to begin revenue operations by mid-1982 in the city of Lille, France. In this system all of the train control systems are fully automated. The individual train modules operate under the sole control of the different automated operational, safety and supervisory control functions. No attendants are planned to be on board, or at the stations, except for security personnel. As with the Japanese systems, the train control system consists of three subsystems, operation, safety, and supervisory oriented controls.

The operation control subsystem consists of sensors to detect aluminum plates, which are at equidistant intervals in the guideway, and electronic equipment to check and control the train's performance against set standards. Under normal circumstances, the vehicle's sensors, when the train is moving, should detect aluminum plates in the guideway every 0.33 seconds. This performance is checked against pulses received from a master clock. The master clock emits a timing pulse every 0.33 seconds. By comparing the number of plates detected vs. the number of pulses received, the operation control can determine if the train is ahead or behind schedule, and change the train's performance accordingly. Station stops are programmed into the station control logic located at each station.

The safety oriented control consists of over-speed protection, train separation, and traffic direction safety. The overspeed protection relies on the rate at which the aluminum plates are detected. When the rate exceeds the preset value, emergency brakes are applied. The train separation also relies on the aluminum plates feature. Each train counts the plates along the route, calculates its position along the track and transmits its position to other trains along the guideway. The receiving train then calculates the distance to the train ahead, compares the distance with the stopping distance for its current speed, and determines whether or not to apply emergency braking. This system is reinitialized every 4 km. section, with each section operating independently. Each section has a check-in/ check-out feature which counts trains entering and leaving.

The traffic direction safety monitors the direction of travel of each train. The system operates on the fail/safe mode by comparing the different frequencies assigned to each direction of travel. When these frequencies do not match, emergency brakes are activated.

The supervisory function, except for performing fleet management and intervening during emergency situations, does not play an active role in the normal operation of the system. The basic purpose of this function is to monitor the functioning of trains and stations. In an emergency, this function can:

- instantaneous shut-down of the trains,

- start up and control the approach procedure of a functioning train to a malfunctioning train, and

- establish provisional services on a part of the line.

3.2.4 Comments on Fully Automated Systems

The fundamental difference between the three systems described above is their operating philosophy. The Japanese have retained a train attendant. The attendant duties, however, are very limited as they are restricted to door operation and passenger assistance during emergencies. In the VAL system, all the vehicle/train controls are automatic.

These systems differ from the most automated U.S. systems in the way train separation is accomplished. In the U.S. this function is performed by wayside signal circuits (see section 4.2.1) which senses trains on segments of track (block) under its supervision and signals the occupancy status of the block. In the foreign systems, this function is accomplished by having the trains broadcast their positions and read the position of trains ahead.

3.3 System Selection

All of the systems discussed in this chapter have functions which have been automated. However, the degree of automation and human involvement differs, ranging from situations in which the operator can totally overrule the automated function to situations in which there are no operators present. The different systems and their degree of automation are compared in Table 3-1.

Of all the automated rapid rail transit systems previously covered in this report, only one (BART) operates with minimum operator assistance. Two other systems presently in operation (WMATA and MARTA) are also highly automated. These systems represent the highest level of automatic operation practiced in the United States. Of these, BART and WMATA have been in operation for several years, and thus, because of their experience, their operational procedures were examined to gain insights into automatic train operation under extreme conditions.

Table 3-1
SUMMARY OF AUTOMATED FEATURES OF SELECT OPERATING SYSTEMS

	TRAIN PROTECTION			TRAIN OPERATION				TRAIN SUPERVISION
	TRAIN SEPARATION	OVERSPEED PROTECTION	INTERLOCK	SPEED REGULATION	STATION STOPPING	DOOR OPERATION	DEPARTURE	
CTA	A•	M	M	A•	M	M	M	M
PATCO	A•	A•	A•	A+	A+	M	M	M
BART, WMATA, MARTA	A	A	A	A+	A+	A+	A	A+
KOBE AND OSAKA	A	A	A	A	A	A+	A	A+
VAL	A	A	A	A	A	A	A	A+

M = MANUAL
A• = AUTOMATIC SIGNAL
A+ = OPERATOR ASSISTED
A = FULLY AUTOMATIC

4.0 IMPACT OF EXTREME CONDITIONS ON TRAIN SAFETY

In order for ATC systems to function properly, three criteria must be satisfied. These are: signal integrity; electrical power integrity; and servo mechanism and ancillary equipment integrity for implementation of instruction that result from these signals.

Although ATC systems are reliable, and designed to fail in favor of safety, that is, bring the train to a stop, interference with any of the three conditions required for proper ATC functions degrades the system's ability to maintain the desired level of performance. Since one of the duties of the ATC is maintaining the safety of the train, degrading its performance may threaten the safety of the train. In addition because the system is unable to completly monitor the train's environment, events outside the range of detection of the ATC system can be detrimental to the safety of the train as the system will not react to these new conditions.

There are two types of interference: 1) internal or resulting from within the ATC system, and 2) external or resulting from the environment. Internal interferences are the least serious as they may be nullified by preventive maintenance of the ATC. Environmental interferences because they occur outside of the boundaries of the rapid rail system, and as such can not be prevented from occurring or detected by the ATC system, can be damaging to the train safety. In the following sections the presence of environmental interferences will be examined to identify what impact, if any, they have on the ATC system. However, since environmental conditions appear in a wide range of intensities, only the worst case condition will be considered. In addition, three other abnormal conditions are examined, these are: internally induced ATC failures; simultaneous internally induced ATC failures and extreme environmental conditions; and overloading conditions. For conditions which are found to be detrimental to train safety, this section makes recommendations to lessen their impact. These recommendations are listed at the end of this section.

4.1 Impact of Extreme Environmental Conditions on Rapid Rail Transit Safety

Environmental conditions result in either accumulation of water, electrical discharges or a movement of mass. In the worst case, these manifestations are more pronounced, and result in floods, hurricanes, deposition of ice and snow, and intense electrical discharges.

The following extreme environmental conditions will be considered in this report: high winds; floods; sub-freezing temperatures, heavy ice and snow; and lightning. Other conditions such as rain, hail, and sleet are not considered because their impact on train safety is similar to the events listed above. The impact of these conditions on the ATC subsystem is shown in Table 4-1. The analysis leading to these conclusions is presented in the following sections.

4.1.1 Impact of High Winds

Although high winds do not impact any of the three criteria required for proper ATC operation, it can impact the train safety in other ways. It can deposit debris on the right of way which when the train passes over might be thrown against the underside. Upon impacting the equipment and wiring it may cause short circuits. This may lead to electrical fires. In addition, winds impose a load on the train suface areas. Depending on the direction of the wind with respect to the train, and the pressure exerted on the vehicle, it may have a detrimental effect on the train safety.

Table 4-1

THEORETICAL EFFECT OF EXTREME ENVIRONMENTAL CONDITIONS

SUBSYSTEM	HIGH VELOCITY WIND	FLOOD	SUB-FREEZING TEMPERATURE	& HEAVY ICE	LIGHTNING
Safety Oriented	N/A	Servo-Mechanism	Servo-Mechanisms		N/A
Operation Oriented	N/A	Servo-Mechanism	Servo-Mechanisms		N/A
Supervision Oriented	N/A	N/A	N/A		N/A
Support Oriented	N/A	N/A	N/A		N/A

To assess the impact of high winds on train safety, overturning moments due to lateral wind forces were determined and analyzed. Details of these calculations are presented in Appendix A. These calculations were made for two cases. In the first case, the wind direction is considered to be perpendicular to the side of the body of the train, and the train is assumed to be on a straight section of the track. In the second case, the train is assumed to be moving on a horizontal curve, and the wind direction is considered to be in the same direction as the centrifugal force. The results of these calculations which were made utilizing vehicle and track data from WMATA and BART, is presented in Table 4-2. On straight sections of the track, the weight of the vehicle is more than enough to compensate for the train overturning due to the lateral wind load. However, on horizontal curves, the imposition of a lateral wind load, when it is in the same direction as the centrifugal force, imposes restrictions on the speed at which the train can move through the curve. Exceeding these speeds may cause the train to overturn under these conditions.

4.1.2 Impact of Floods

The presence of water on the rails has a detrimental effect on the ATC's ability to stop a train. This is due to the fact that wet surfaces have lower adhesion characteristics than dry surfaces. Figure 4-1 shows an estimate of the distance required to bring a train to a complete stop at various speeds. Details of these calculations are presented in Appendix B. From the graph it can be seen that the presence of water on the track more than doubles the distance necessary to stop a moving train. Thus, in an emergency, as when there is a stopped train on the track, a train trying to stop in these conditions could quite easily overshoot the distance between it and the train ahead. In addition, if the water level is much higher than the ball of the running rail, it will decelerate a moving train at a much faster rate than is safe. Thus, passen-

Table 4-2

IMPACT OF HIGH WIND

SYSTEM	HORIZONTAL STRAIGHT TRACK	HORIZONTAL CURVE	
		Maximum Safe Speed	
		High Wind*	No Wind
WMATA	No Impact	33 MPH	45 MPH
BART	No Impact	31 MPH	71 MPH

* Wind Speed 80 MPH Wind Lateral Load 35 psf

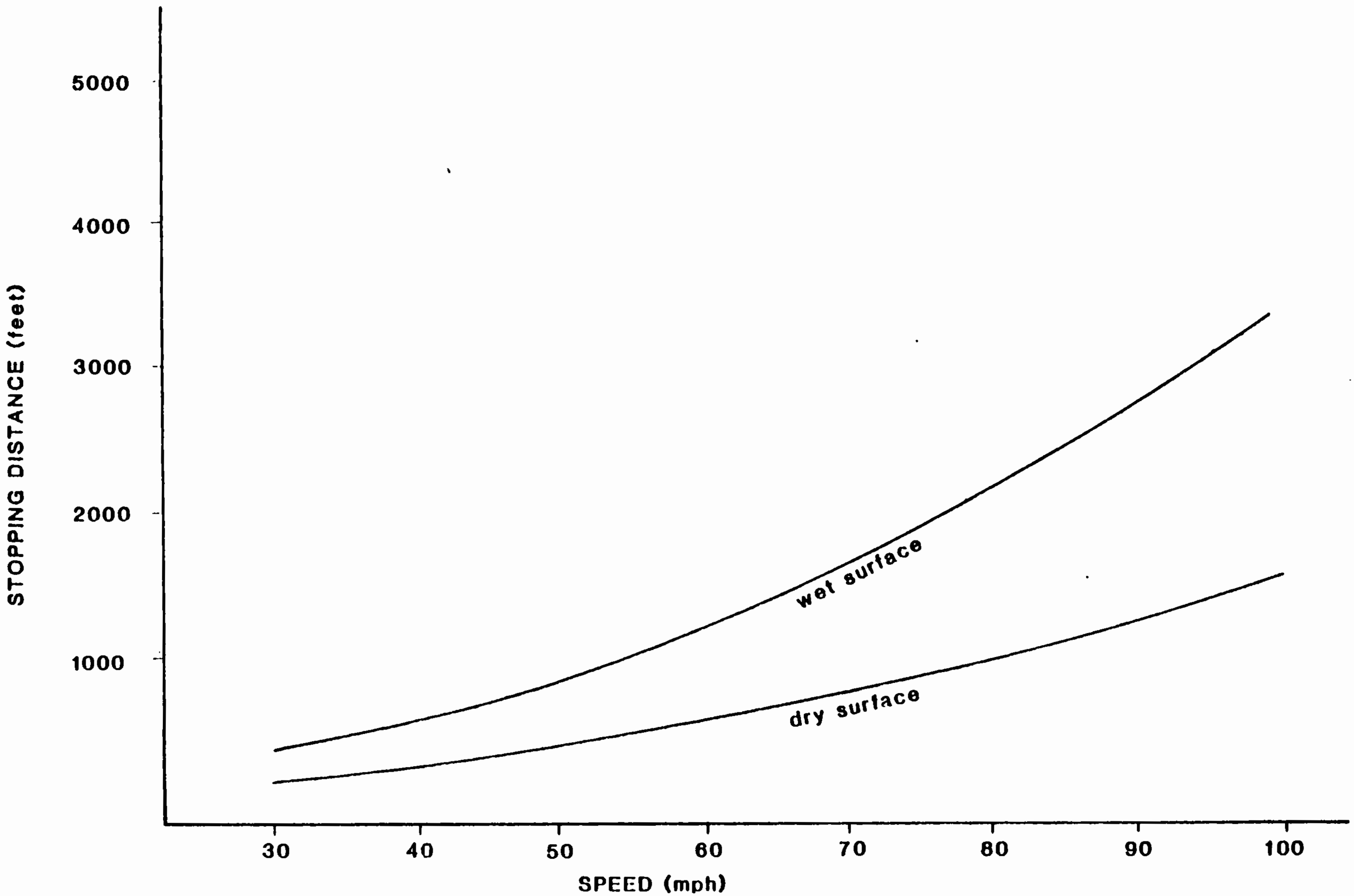


Figure 4-1 STOPPING DISTANCE WET AND DRY CONDITIONS

gers on board would be thrown about at the same speed the train had when it entered the flooded area.

Although it may be possible to operate a train through the flooded area if the third rail has not been affected, doing so would endanger the train's safety. This is due to the fact that although the tracks may be dry, the brakes are inoperative due to the presence of water in the brakes' contact surfaces.

4.1.3 Impact of Heavy Ice and Snow and Sub-Freezing Temperatures

The occurrence of heavy ice and snow, and sub-freezing temperatures which forms ice out of moisture in the air, have a more severe impact on the ATC's ability to stop a train as they reduce the track adhesion characteristics even more than flood conditions do. Whereas under flood conditions, the stopping distance is more than twice what it is on dry surfaces, under icy conditions it is nearly four times as great. This effect can be better appreciated from Figure 4-2, which is the result of calculations similar to the ones for floods. In addition, these conditions degrade the performance of mechanical components of the ATC system. One component which is severely impacted is the switch assembly as the presence of ice and/or snow impedes its normal operation. That is, the presence of either element prevents it, when operated, from properly aligning itself with the rails. Thus, these environmental conditions have a double effect on the performance of the ATC system. On the one hand they increase the distance required to stop a train, which may result in collisions, and on the other by interfering with the normal operation of the switch assembly, they may cause the train to derail.

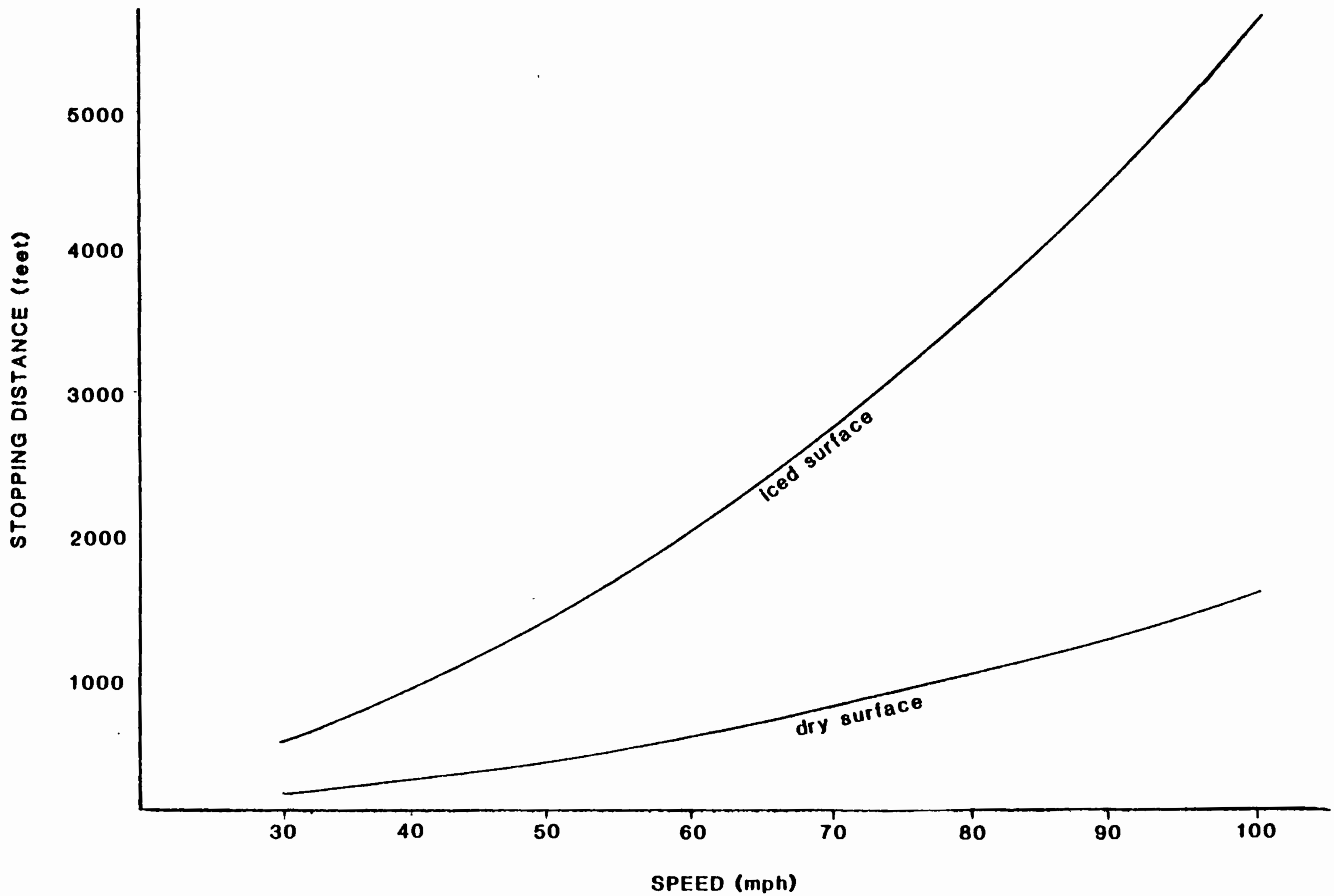


Figure 4-2 STOPPING DISTANCE ICED AND DRY CONDITIONS

4.1.4 Impact of Lightning

In order to assess the impact of lightning on the power distribution and communication system, its effect must be analyzed in terms of the magnitude and frequencies of the harmonies it generates, that is, in terms of the frequencies that are multiples of the fundamental frequencies of these systems. This analysis is presented in Appendix C, where it is shown that the maximum impact of lightning comes at the time when lightning occurs. Furthermore, theoretically, its impact would be of infinite magnitude. If lightning strikes the third rail, the effect would be devastating if the third rail could not withstand the impact. Under these conditions, there would be a sudden increase in the electrical load and an intensification in the strength of the magnetic forces associated with these currents. Conductors carrying electrical currents will exert forces on each other. These forces are caused by the magnetic fields about the conductors. Under short circuit conditions, from the load end, these forces can be of great magnitude, and can result in the busbars deflecting and causing arcing from line to line. However, A.C. power distribution are built of rigid, continuous-beam conductors supported by free sliding hangers which are located at close intervals. Thus the actual stresses resulting from the action of these magnetic forces is absorbed by the supports, consequently, since the integrity of the system is preserved, no arcing occurs. In addition, the power distribution systems are properly grounded, thus a temporal surge of these magnitudes would be quickly neutralized. It remains an issue, however, how to effectively keep conductive debris from getting lodged between the busbars.

Although the frequency distribution may overlap that of the communications systems, it is not deemed to have an adverse effect on train safety. This is because of the even distribution of the impulse frequencies and in light of the fact that instructions to the train concerning speed commands and train detection, are transmitted through the running rail. These instructions are generated at each block, and are continuous. In addition, to minimize interferences, receivers in the train are equipped with narrow band crystal filters to separate signals from noise. Furthermore, the use of frequency-shift keying provides an additional safeguard against interferences. Thus, radio frequencies generated by lightning are effectively removed in transmissions to the train. And in the event of signal loss, the absence of signal is interpreted by the ATC as being a zero speed command. Then, in the event of temporary loss of signal, the communication is quickly restored, or failing that the system will bring the train to a halt.

4.2 Impact of ATC Malfunction

Although failure of ATC components are few and far in between, their failure poses a serious problem to the safety of the train, mainly because its happening denies vital information about the trains surroundings, performance, and/or location, which may cause the train or other trains to operate in an unsafe manner. In the next sections, the different subsystems that make up the automatic train control system will be analyzed to assess their impact on train safety. The analysis will be performed by examining the ATC components according to their main purpose previously discussed in section 2.2 of this report.

4.2.1 Safety Oriented Controls Malfunction

As previously discussed in section 2.2, safety oriented controls are entrusted with protecting the train and its passengers. It accomplishes this by monitoring and correcting the train's performance, and by checking the train's environment for unsafe conditions. The following discusses the malfunctions of these controls:

Train Separation Malfunction

The purpose of the train separation function is to maintain a safe distance between consecutive trains. To accomplish it, this function relies on wayside signals and speed commands. The wayside signals consist of color light signals much like street traffic lights. These are placed beside the track at the entrance of each block and its operation is controlled by a relay, which in turn is operated by the track circuit (see figure 4-3). When the block is empty, the track circuit holds the relay in the up position. In this condition the wayside signals indicate clear or go conditions. When a train enters the block, its wheels and axle connect the running rails, shorting the power source, consequently reducing the current through the relay. This causes the relay to drop as shown by the dashed lines in the figure. Once this happens, the wayside signal indicates occupancy and issues the appropriate speed commands to the preceeding blocks. Depending upon the block length, line speeds involved, and the number of available speed commands, the second block behind the train may have a speed of zero or greater, the third block a commanded speed equal or greater to the second block, and so on. In all instances the blocks behind the train are signaled so that a train entering a block has sufficient stopping distance to leave the block with a speed no greater than the commanded speed. In the case of zero speed command, the train must be able to stop before it comes to the end of the block.

Failure to detect a train may occur for instance as a result of rusty rails, since in this condition the track circuit will not be shunted, or because of outright equipment malfunction. Obviously, failure to detect a train posses a serious safety hazard, specially when the undetected train is not moving, or is moving slowly. Although it may be possible to stop the train on time, it may not be the case as illustrated below. On August 1, 1975, a train operating in an under-

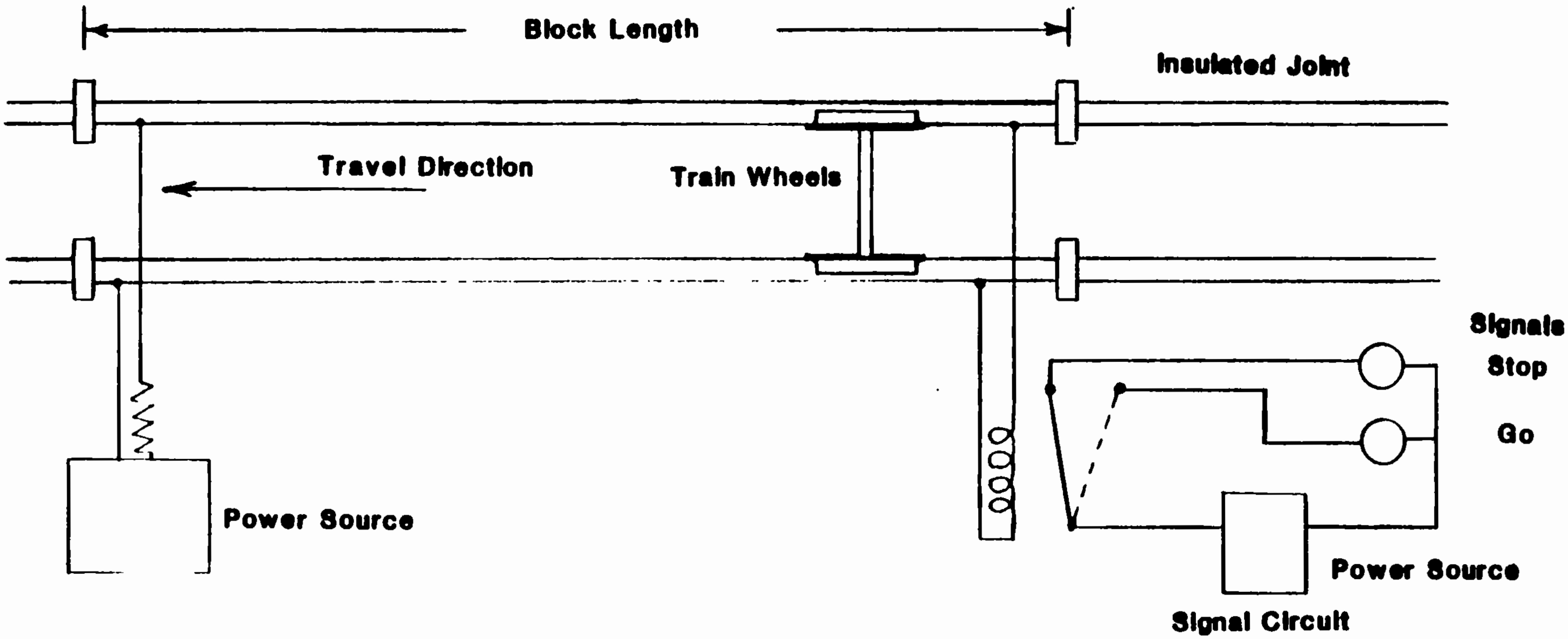


Figure 4-3 SCHEMATIC DIAGRAM OF TYPICAL WAYSIDE SIGNAL CIRCUIT

ground section of the Massachussetts Bay Transportation Authority Red Line, while waiting to be given permission to proceed was hit from the rear by a following train, two minutes later, the second train was struck from the rear by a third train. One hour before these accidents happened, the safety control system for this particular section of track had gone out-of-service, and trains operating in the area were operating under manual rules requiring that the operator proceed with caution, and be prepared to stop within the line-of-sight distance.

From 1965 to 1974, CTA experienced 35 collisions, of these one was attributed to wayside signal failure and human error. In this accident, the train operator failed to notice the malfunction, consequently did not take corrective actions such as slowing down. As the train negotiated a curve in the subway, it hit a standing train because the operator was unable to stop on time. The fact these accidents happen suggests that the operator was not sufficiently alert to the track conditions ahead. Thus, there is a need to implement measures that will insure that the operator will notice, even in the event of signal absence, that there is a standing train on the track ahead.

Overspeed Protection Malfunction

The overspeed protection function is performed basically by three elements: A speed sensing device provides input concerning the actual train speed, a comparator checks the actual speed with the commanded speed and determines if brake application is required, and a brake activating mechanism to limit the train speed to the commanded speed.

It should be noted that the comparator, in checking the speed performance of the train, orders the application of the emergency brakes only after the train speed has exceeded the commanded speed over a certain period of time. If this speed is continuously exceeded, the brakes are applied to bring the train to a stop. In the yards, due to the congestion that exists there, the train is brought to a halt when the limit speed is exceeded. Failure of any of the components that make up the overspeed protection function have a serious impact on train safety because of lack of information on which to act, or because the system is unable to correct an unsafe condition. Overspeeds can be dangerous, as the train may derail if cruising a horizontal curve at too high speeds, or it may result in collision because the train was going too fast to stop within the available distance. In the WMATA system for example, cruising speeds on horizontal curves, as estimated in section 4.1.1 is 45 MPH. At this speed, the overturning moment due to centrifugal forces is balanced by an opposing moment due to the weight of the car. Increasing the speed, however increases the overturning moment, consequently, the train may derail.

Route Interlocking Malfunction

The purpose of the route interlocking function is to safely route the trains through the different tracks in a manner which does not result in conflicting moves with other trains. In order to accomplish the passage of trains safely, the system monitors the presence and location of the different trains approaching the interlock area. This information is obtained from the train separation function. It also monitors information on the status and position of the track switches. In addition, before the system aligns a route, it determines if the proposed route is not in conflict with an existing route for another train. If no conflict exists, the appropriate track switches are positioned, and their positions verified. Then each switch is immobilized and locked until the passage of the train has been verified.

Failure of the interlock to perform properly has serious consequences as it may cause the train to derail or collide with another train. This may occur for instance when the mechanical components of the interlock are blocked by ice, or debris which impede positive switch closure, or by power failure as was the case in the derailment that occurred in the WMATA system in January 1981. In this accident, a power failure due to an open fuse, incapacitated Central Control from operating the switch. Subsequent improper manual operation of the switch resulted in the accident.

4.2.2 Operations Oriented Controls Malfunction

The operation oriented controls are concerned with the performance of the train when in main-line service. As such, it regulates the train speed, its alignment at station platforms and monitors the operation of doors.

Speed Regulation Malfunction

The purpose of the speed regulation function is to adjust the train speed according to operational needs, that is, accelerate/decelerate to maintain a prescribed schedule. A malfunctioning speed regulation unit can cause the train to accelerate when the opposite has been commanded. In this case, the overspeed protection system, if operational would restrict the train speed as needed, if the operator has not taken corrective action in the time allotted him to do so. An accident which was attributed to a malfunctioning speed regulator occurred in 1972 at the BART Fremont station. In this accident, a faulty crystal oscillator in the speed control electronics caused the train to speed up when it should have slowed down to enter the station. Before the operator could react, the train ran off the end of the track and derailed.

Platform Line-up Malfunction

No safety related issue is envisioned in the failure of the platform line-up function.

Door Control and Starting Malfunction

The purpose of the door control and starting function is the operation of the doors at stations, and the starting of the train at departure time. On starting, four conditions should be met before the train exits the stations: 1) the door should be closed and locked; 2) no passenger should be caught at the doors; 3) it should be time to depart; and 4) it should be safe to move the train. Although meeting these conditions insures the safety of the passengers, no door system is fool proof. For this reason, all U.S. rapid rail transit systems have operators to monitor and operate the door and act as back up to insure that the train does not depart while passengers are boarding or leaving, and to verify that no one is caught when the doors are closed and locked. Failure of the door to close properly then causes the train not to depart. However, under some circumstances, as when thin material is caught between the door, the locking mechanism may not fully secure the doors, and may even release them when the train is moving. If this happens, the emergency brakes are activated and the train is brought to a stop. Apart from being a hazard to passengers, it also disrupts schedules.

4.2.3 Supervisory Oriented Controls Malfunction

The supervisory oriented control function is not deemed to have a detrimental impact over the safety of the train. This is because it comprises a set of functions concerned with the overall management of traffic and the operation of the system as a whole, thus, the supervisory function is strategic, system wise, and long term. In addition, any conflicting instructions issued from this function are checked by the safety oriented controls, and overruled if found conflicting with train safety.

4.2.4 Support Oriented Controls Malfunction

No safety implication as this function is the most removed from actual train operations.

4.3 Impact of Simultaneous Internally Induced ATC Malfunction and Extreme Environmental Conditions

As discussed previously in this section, ATC failures are either internally or externally induced. Although internally induced ATC failures are not, in general, the result of environmental conditions, it is possible that they may occur in coincidence with extreme environmental conditions. In this event, the safety of the train is impaired even further as two factors detrimental to train safety are acting concurrently. On the one hand, environmental conditions limit the ATC's ability to stop the train, on the other, ATC failures deny information concerning the track occupancy status and expected train performance. Thus in the event of ATC internally induced failures, the safety of the train depends on the operator. However, because extreme environmental conditions degrade the performance of the servomechanisms and ancillary equipment it may not be possible for the operator in an emergency, to modify the trains performance to avoid a disaster. For instance, the trains operational speed is determined by the profile of the track ahead of the train, that is, slower speeds when approaching stations, horizontal curves, etc. If for example, the speed regulation function fails to direct slower speeds when approaching a horizontal curve, and instead accelerates the train, and the tracks are under icy conditions, efforts by the operator to stop or slow down the train will have no effect and the train may derail as a result of approaching the curve too fast. Similarly, a failure in train separation function combined with, say flooded tracks, may cause a collision to occur if there is a standing train on the track ahead. This is because the operator will not become aware of the occupancy conditions until the disabled train is within the line-of-sight, and the distance separating the two trains may be too short, under flood conditions, to avoid a collision.

4.4 Impact of Overloading

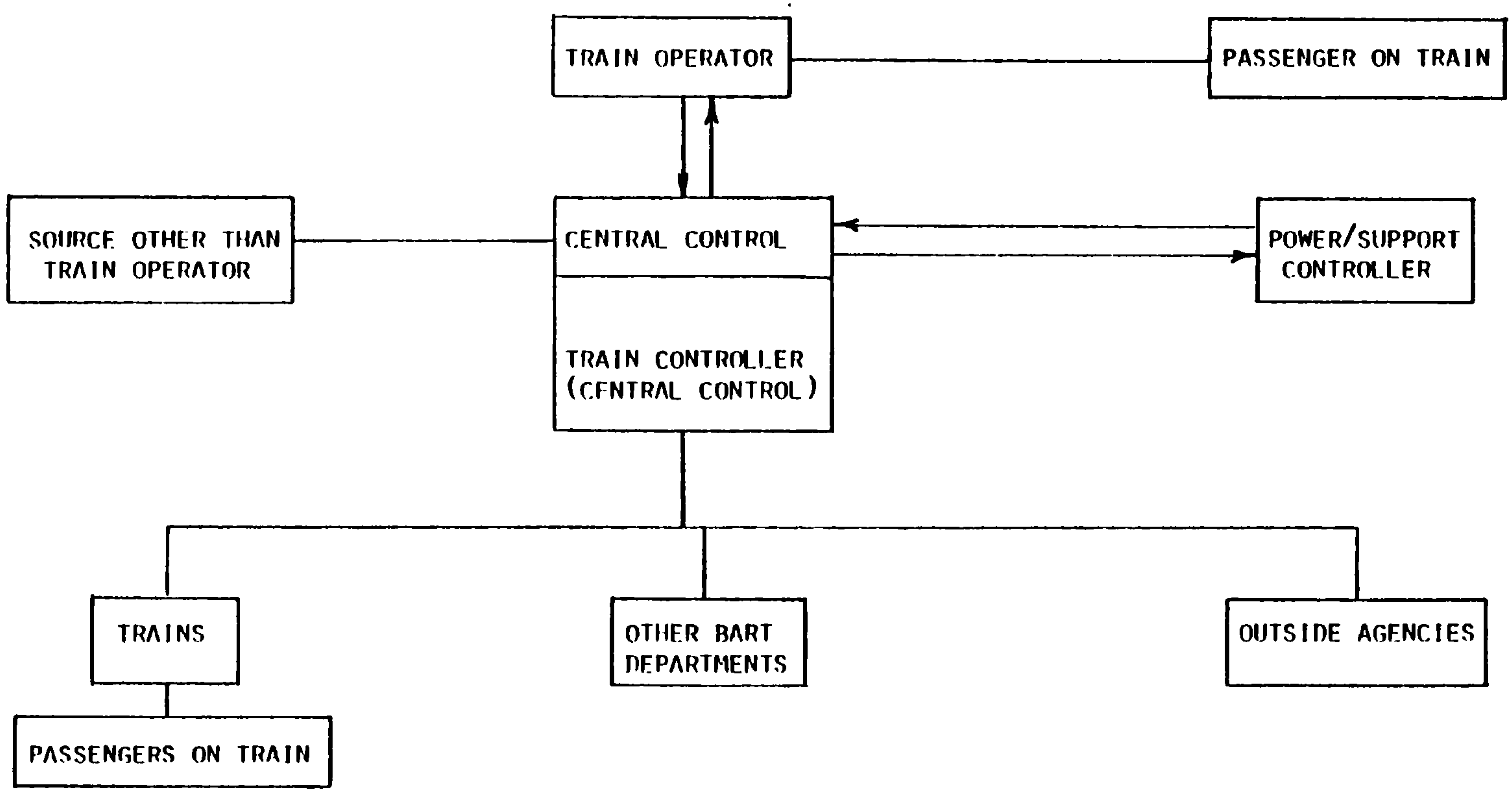
To ascertain the impact of overloading on train safety, several transit properties were surveyed. These were BART, WMATA, CTA, NYCTA, and PATCO. Our findings indicate that this condition does not pose a safety hazard, in fact, for one property (NYCTA) it is not even an operational problem as the trains continue to operate regardless of the number of passengers on board. For properties with trains equipped with door control and train starting systems, overloading causes a problem insofar as delaying train departure if blockage of the door occurs. As discussed in section 2.1.1 this system starts the train after the doors are closed.

4.5 System Management During Extreme Conditions

In order to react to any anomalous situation, the condition must first be detected and analyzed to assess its severity and the level of response called for. To gain insights into present day practices, the flow of information in each of the abnormal situations is discussed for high winds conditions, flood, heavy ice and snow and subfreezing as well as for ATC malfunction conditions for each of the two properties covered.

4.5.1 High Wind Condition

Figure 4-4 highlights the flow of information for the BART system when a high wind condition is known to exist, or is reported by an operator or other source. The WMATA system,



SOURCE: MODIFIED FROM BART EMERGENCY PLAN

Figure 4-4 BART SYSTEM EMERGENCY INFORMATION FLOW CHART HIGH WINDS which operates in the nations capital, is not included since this system does not consider high winds to be detrimental to the safety of its trains.

In the BART system the operator is required to stop the train, and request, from Central Control, permission to operate manually, if the operator feels that cruising speeds, in the automatic mode, are too high for the stopping distances that may be required due to debris falling on the track. Central Control is required to declare out-of-service any area which has been severely impacted.

4.5.2 Flood Condition

Figures 4-5 and 4-6 show the flow of information for BART and WMATA when a flooding condition is reported. Two different reporting methods are utilized by these systems: automatic alarms and visual inspection. The former reporting method is utilized by BART, while the latter by WMATA. In the BART system these alarms are activated by sump pumps and line sumps when the water reaches certain critical levels. In the case of sump pumps, the alarm is sounded, when there is a loss of power of their activating relay. In addition, BART employees are required to notify Central Control if they become aware of potential flood conditions.

Once Central Control has been notified, and it has elucidated all the facts concerning the flood, Central Control notifies the appropiate BART personnel and outside agencies, de-energizes the third rail, and classifies the area as the "emergency scene". Train traffic is not permitted to go through it, and service will be restored only after the area has been released by the On-Scene Coordinator. The On-Scene Coordinator may be a Power and Way supervisor, or Line/Transportation supervisor depending upon the conditions at the scene at any given time. When acting as the On-Scene Coordinator,

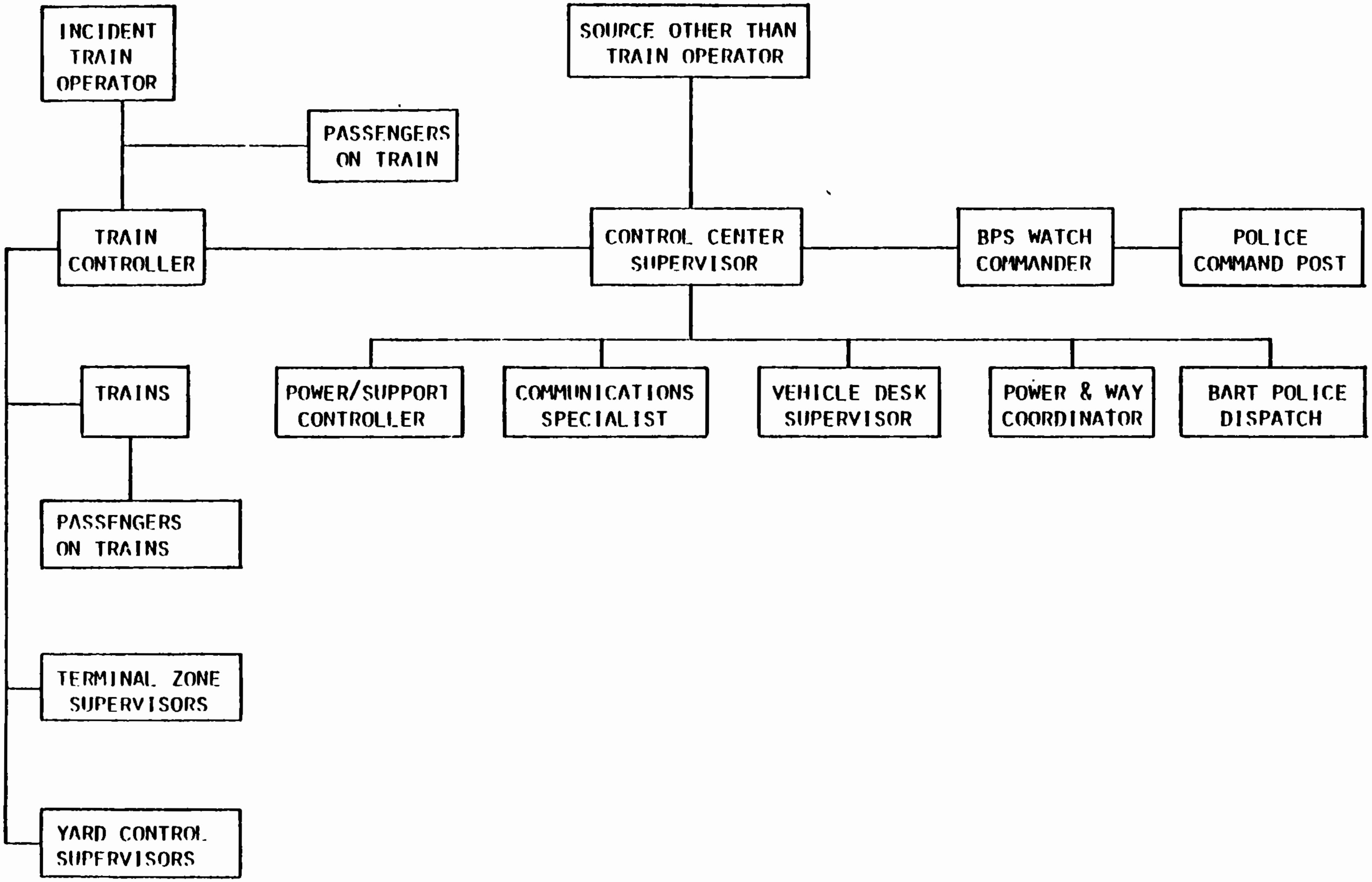
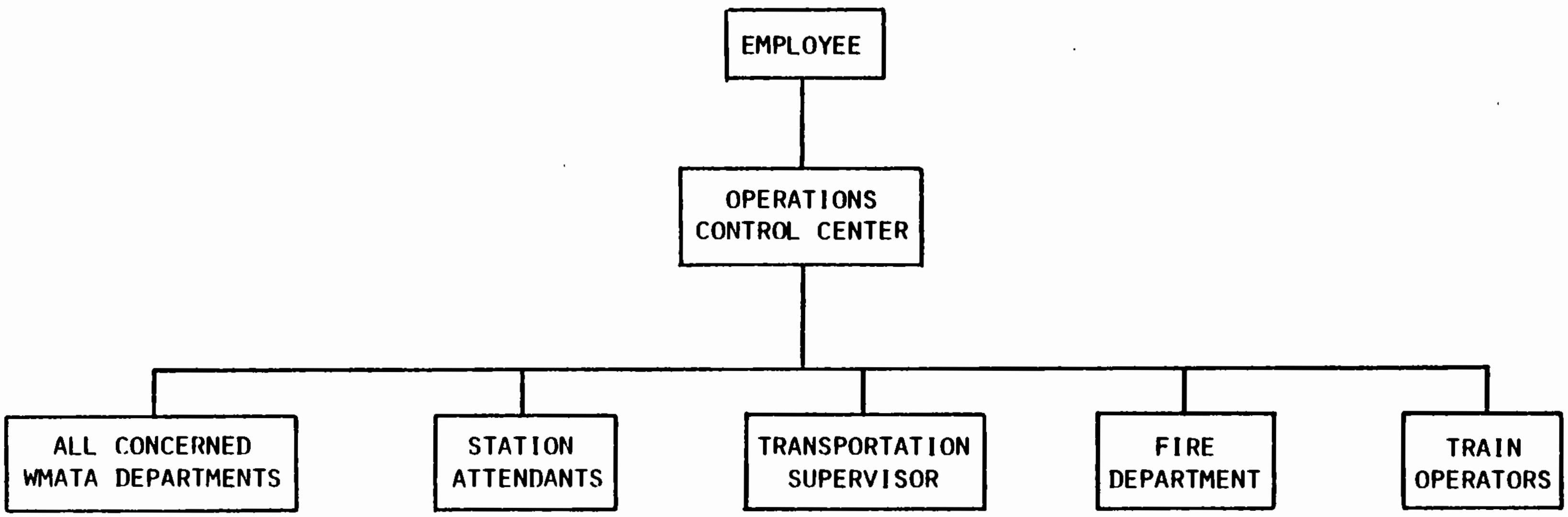


Figure 4-5 BART SYSTEM EMERGENCY INFORMATION FLOW CHART FLOODING

SOURCE: MODIFIED FROM BART EMERGENCY PLAN



SOURCE: PREPARED FROM WMATA OPERATIONS MANUAL

Figure 4-6 WMATA SYSTEM EMERGENCY INFORMATION FLOW CHART FLOODING the Power and Way supervisor is concerned with facility restoration, and the Line/Transportation supervisor with service restoration.

In the WMATA system, the procedure is a two level response. In both cases, the Transportation supervisor must be present to coordinate all WMATA activities at the scene, and cooperate with the Fire Department officials if they are present. Train operators, or any other WMATA personnel who notices a flooding condition, are responsible for notifying Central Control.

If the water level is below the ball of the running rail, trains are instructed by Central Control to proceed through the area at restricted speeds in mode 2. (Mode 2 refers to manual train operation with automatic speed control checks.) Upon arrival to the first station stop after clearing the flooded area, operators are to switch back to mode 1, and inform Central Control the condition of the area they passed through. (Mode 1 of operation refers to automatic train operation).

When the water level is above the ball of the running rail, Central Control prevents all trains approaching the incident area from entering. Furthermore, all trains are instructed to wait outside the bounds of the area until further notice. After the trains are positioned, the third rail power is removed, the fire department is called in to assist in removing the water. In addition, Central Control initiates procedures to ease train congestion, requests bus shuttle service, and if feasible starts single track operation through the area.

4.5.3 Heavy Ice and Snow and Sub-Freezing Temperatures Condition

Neither of the systems covered in this study experience these conditions with any great frequency, one system (WMATA) however, suffers from unusal amounts of snow during the winter months. These occurrences are sporadic, but serious enough to warrant appropriate action to maintain the system operational. WMATA's procedure is outlined below.

Figure 4-7 shows a schematic diagram of the information flow when unusual amounts of snow are forecasted or when an unexpected storm occurs. If the storm is forecasted, WMATA retains all its operating and maintenance personnel at strategic locations ready to clear the tracks and stations of any snow or ice accumulation. Once there is accumulation, extra trains are ordered to run on the exposed sections of the track, track switches are operated frequently to insure that they stay functional during the duration of the condition. In addition, switches are equipped with resistance heaters to keep them above the freezing temperature. This precaution prevents accumulation of ice.

4.5.4 Lightning Condition

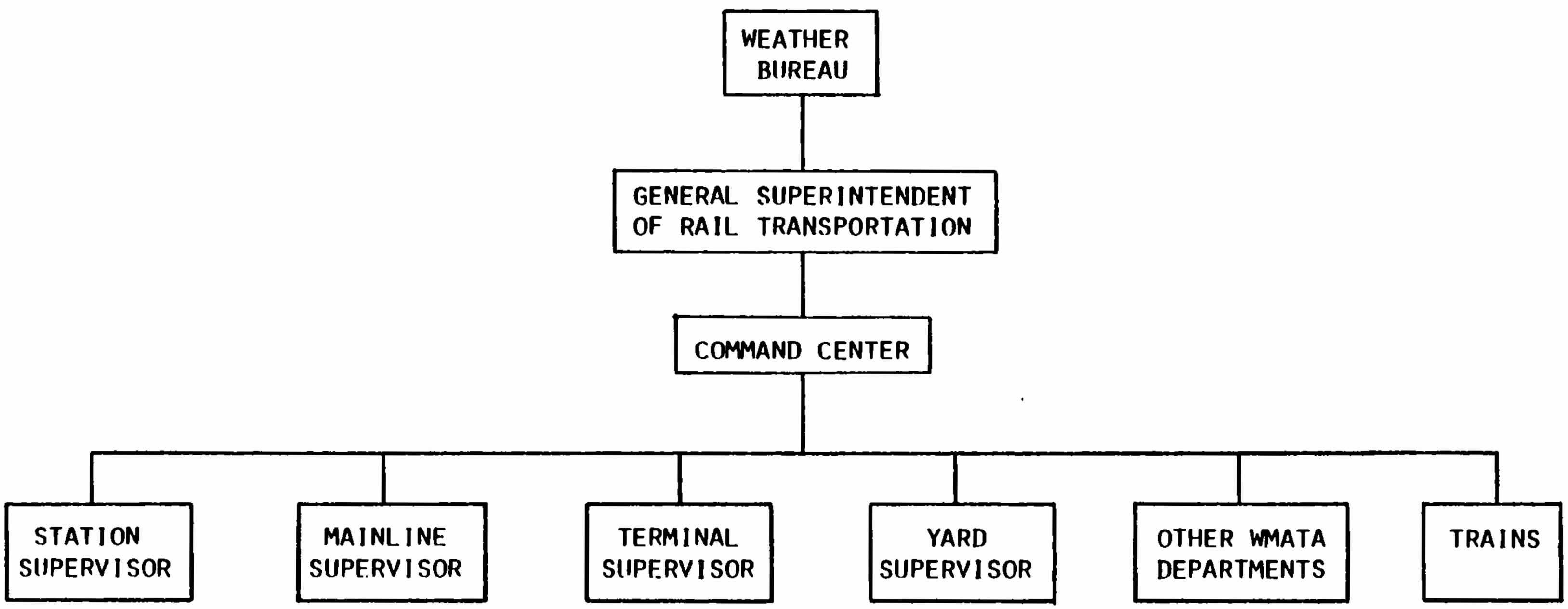
Neither of the systems covered in this report considers lightning to be a threat to either train operation or safety.

4.5.5 ATC Malfunction Condition

All the properties studied in this report responded similarly to this condition, their response, however depends on the severity of the condition. For instance, a train operating with 90% brake capacity would not trigger a response, but a train with brakes unoperational would call for an immediate removal of the train to the service area.

4.5.6 Overloading Condition

The various systems surveyed respond differently to this condition. In systems in which the train will not start be-



SOURCE: PREPARED FROM WMATA OPERATIONS MANUAL

Figure 4-7 WMATA SYSTEM EMERGENCY INFORMATION FLOW CHART
HEAVY ICE AND SNOW AND SUB-FREEZING TEMPERATURE

cause of open doors, the problem is solved by asking the passengers next to the door to wait for the next train. This duty is regularly performed by station employees.

4.6 Conclusions and Recommendations

Extreme conditions, internal or external, can degrade the performance of ATC systems. This can occur in either of two ways: by changing the track conditions to a condition the system is not aware of, or by actually interfering with the ATC proper functioning. In either case the safety of the train is impaired and that is either because of reduced level of train control, or because of less time in which to react, or both. In the event that they occur, whether simultaneously or separately, actions by the train operator to prevent collisions and/or derailments may have little or no effect.

The transit properties analyzed in this study emphasize train safety insofar as automatic equipment malfunctions. The response is the same in all these systems. With respect to abnormal environmental conditions, they react differently. Obviously, there is no need to be prepared for all the different conditions since not all the geographical locations in the country experience them. Some of these conditions (high winds and floods), however, are found across the United States. Yet, the degree of response varies considerably from system to system, from stopping the train and proceeding at reduced speeds, to completely ignoring the fact that the condition exists, even though these conditions are equally severe in magnitude and can cause extensive damage to the train.

The procedure for reporting the occurrence of abnormal situations, except for floods, is similar in the two transit systems. For flood conditions BART employs alarms which are activated by the water level, whereas WMATA resorts to visual inspection to ascertain if the condition exists. It should be noted that under this mode, the checks are performed periodically, and that in between checks, a flooding condition may take place, or if already present, may grow in magnitude.

In order to minimize the impact of abnormal environmental conditions on train safety the following is recommended.

High Wind Condition

It is recommended that when wind speeds reach 39 MPH, trains should slow down and be operated under semi-automatic controls, until the condition has passed. This recommendation is made in light of the fact that at this wind speed, there is a strong possibility of debris falling on the right of way, and as indicated previously, the debris may cause undercar fires.

Since the same wind speed is not felt everywhere at the same time, it is recommended that the responsibility for the decision to proceed at the operational speeds, be left to the train operator because since the operator is at the scene, he can decide, based on visual observation, if the winds are too strong.

Flood Condition

It is recommended that checks for flooding be performed automatically by a system of pumps, and that the pump system notifies the station having control over the track affected and Central Control. Furthermore in order to insure that the area involved is cleared as soon as possible, traffic through the area should be stopped until all repairs have been made and the water has been drained-off. In addition, the third rail power should be removed as soon as practical.

Heavy Ice and Snow and Sub-Freezing Temperatures Condition

It is recommended that whenever this condition exists, track switches be kept operational by frequent manual activation. In addition, to insure that they stay in an ice free condition, they should be equipped with heaters. Furthermore, visual signals associated with their operation should be operational, and cruising speeds when approaching them, should be reduced so as to insure the train will be able to stop in case the switches, because of ice, are not functioning properly. In addition, the track should be kept operational by the use of snow and ice clearing equipment, and by running trains, at safe speeds, over the affected sections of the track.

Collisions and Derailments

The analysis of the previous sections indicates that almost all the extreme environmental conditions and operation and safety oriented control failures lead either to collisions or derailments. In addition, since in automated systems, the operator is the safety control of last resort, it can be said that if the operator has been alert, some if not all of these accidents could have been avoided.

Since collisions and derailments happen as a result of equipment malfunction, or because of adverse conditions in the track, the following is recommended to reduce the likelihood of collisions and derailments.

For Collisions

- Installation of police type light in a highly visible part of the train. The operation of this device should be manual from the cab.

- In sections of the track with short line-of-sight installation of one or more police type lights at area entrance. These should be activated automatically as the train enters, and deactivated as the train leaves the area.

<u>For Derailments</u>

Switches should be inspected daily for:

- Power failure
- Visual signal failure
- Automated Controls failure
- Mechanical integrity

5.0 FIRE PREVENTION AND CONTROL

Ideally the best state-of-affairs is to have no fires at all. However, due to the difficulty of safeguarding against all the factors that play a role in starting one, the next best thing to do is to minimize the risk of having one, or once a fire has started, to keep it from propagating. This section examines the origin of train fires, evaluates the materials used in the fabrication of trains, and makes recommendations to improve the train safety.

5.1 Origin and Path of Fires

Due to vehicle design, there are two major sites at which a fire may start. These are, the vehicle under carriage, where most of the mechanical and electrical components of the ATC are located, and the vehicle interior. The latter, because of weight and aesthetic considerations, contains the major part of the synthetic materials found in the vehicle. Also, it is here where readable and other flammable material, discarded by the passengers, is found.

Vehicle interior fires are usually the result of acts of vandalism, and are more serious than undercar fires. This is due to the fact that once the inside is ignited, the integrity of the entire consist is compromised as the fire may extend to other cars by way of the roof.

There are two major causes of vehicle undercarriage fires: 1) servomechanism failures, and 2) electrical power failures. The prime example of servomechanism failures is that of the friction brakes overheating. Since this unit converts the vehicle's kinetic energy into heat, the generated heat may be enough to ignite the insulation of cables located nearby. Ignition of these cables may breach the floor/wall junction, thus allowing the fire to spread upward by way of the ductwork and liners located in the walls.

Electrical power failures may result from debris being thrown against the undercarriage, damaging the wiring associated with the electrical equipment, or from outright failure of these equipment. For instance, heater resistors, due to the vehicle motion may shake loose, and come in contact with each other, causing sparks which in turn may ignite the insulation. This in turn may burn a hole in the floor, allowing the fire to spread to the vehicle inside. Table 5-1 shows a list of potential fire sources found in the vehicle undercarriage.

5.2 Evaluation of Vehicle Interior Materials

Many different materials are used in the manufacture of rapid rail transit vehicles as evidenced in Table 5-2. These materials are utilized alone or in conjunction with others. Their advantages/disadvantages when exposed to fire conditions are explored in the following sections. Other materials although not presently utilized in the industry are included because of their apparent potential for utilization.*

Plastics

Although the flammability of plastics is not thoroughly documented, some plastics are known to withstand fire conditions better than others. In general, the flammability of plastics is a function of chemical composition, that is, the presence of certain chemical elements such as chlorine, nitrogen, etc., improves the plastic's ability to resist fire. The fire and other physical characteristics of plastics is shown in Table 5-3. Fire retardant coatings, although not a plastic, is

* UMTA is in the process of developing material selection guidelines, and has developed flammability and smoke guidelines.

Table 5-1

VEHICLE UNDERCARRIAGE POTENTIAL FIRE SOURCES

VEHICLE COMPONENT	POTENTIAL IGNITION SOURCE
COLLECTOR SHOE ASSEMBLY	IMPACT OF DEBRIS ON THE RIGHT-OF-WAY WITH THE COLLECTOR SHOE ASSEMBLY COULD POSSIBLY BREAK OFF THE MOUNTING ASSEMBLY FROM THE TRUCK FRAME SUPPORT, PERMITTING THE COLLECTOR SHOE TO CONTACT THE CAR BODY. THIS COULD RESULT IN ARCING AND IGNITION OF INSULATION.
LINE SWITCH BOX	EVEN THOUGH CONTAINING HIGH VOLTAGE POWER TO THE CAR, THERE SHOULD BE NO FIRE HAZARD IF NO FLAMMABLE MATERIAL IS INSIDE OR NEAR IT.
LINE REACTOR	THIS UNIT IS AN OPEN CORE INDUCTOR DESIGNED TO REDUCE RIPPLE CURRENTS PRODUCED BY PROPULSION CURRENT FLOWING IN THE RUNNING RAIL. THIS UNIT COULD PRESENT FIRE HAZARD IF IT OVERHEATS OR ARCING OCCURS.
SEMI CONDUCTOR BOXES	HIGH VOLTAGE IN CIRCUITRY COULD PRODUCE ARCING AND POSSIBLE IGNITION OF WIRE INSULATION OR DIELECTRIC OIL IN CAPACITORS.
MOTOR CONTROL BOXES	HIGH VOLTAGE WITHIN THE UNIT WHICH CONTAINS SWITCHING DEVICES OF THE PROPULSION CIRCUITS COULD PRODUCE ARCING AND POSSIBLE FIRE OF INSULATORS OR OTHER MATERIAL.
PROPULSION BLOWER	MOTOR PROVIDING FORCED VENTILATION COULD ARC WITH LUBRICANT WITH LITTLE IMPACT OF FIRE.
TRACTION MOTOR	HIGH VOLTAGE MOTORS VENTILATED, BUT MALFUNCTION COULD RESULT IN SHORTS WHICH COULD RESULT IN FIRE IF IT CONTAINS INSULATING RESINS AND POTTING COMPOUNDS.
DYNAMIC BRAKING RESISTOR	GRIDS OF RESISTORS ARE USED TO DISSIPATE ENERGY PRODUCED BY TRACTION MOTOR WHEN CAR IS IN DYNAMIC BRAKING MODE. ELECTRICAL ARCING TO GROUND FROM HIGH VOLTAGE GRID IS POSSIBLE WITH POTENTIAL FIRE TO THE SURROUNDING MATERIAL.
FRICTION BRAKE ASSEMBLY	MALFUNCTION OR UNUSUAL HIGH NUMBER OF HEAVY BRAKE APPLICATIONS COULD OVERHEAT BRAKE PADS PRODUCING SMOKE. FIRE IS POSSIBLE IF FLAMABLE SURROUNDING MATERIAL IS PRESENT OR BRAKE FLUID IS LEAKING FROM BRAKE LINES.
HYDRAULIC POWER UNIT	UNIT CONTAINS PUMP AND MOTOR, CONTROL VALVES AND SWITCHES, AND FLUID RESERVOIR. FIRE IS POSSIBLE IF PUMP MOTOR IS FAULTY CAUSING BURNING OF MOTOR WINDINGS OR HYDRAULIC FLUID.
BRAKE CONTROL UNIT	THIS UNIT HAS A LOW PROBABILITY OF CAUSING A FIRE EVEN IF THE BRAKE FLUID LEAKS AS IT OPERATES WITH LOW VOLTAGES.

Table 5-1 Continued
VEHICLE UNDERCARRIAGE POTENTIAL FIRE SOURCES

VEHICLE COMPONENT	POTENTIAL IGNITION SOURCE
PARKING BRAKE UNIT	USUALLY LOW ELECTRICAL ENERGY IN COMPONENTS, BUT IN CASE OF FAULTY RELAYS OR SOLENOIDS, AND PRESENCE OF LEAKING BRAKE FLUID, THERE IS POSSIBILITY OF IGNITION OF FLUID.
MOTOR ALTERNATOR	INTERNAL FIRE IS POSSIBLE IF MOTOR IS FAULTY AND FLAMMABLE MATERIAL IS NEAR BY.
ELECTRIC AUXILIARY UNIT	OVERHEATING OR SHORT IN CIRCUITS COULD IGNITE SURROUNDING MATERIAL IF FLAMABLE, AND IF DEFECTIVE OR UNPROPER FUSES ARE USED.
BATTERY	FIRE COULD DEVELOP IF IMPROPER VENTING IS ALLOWED AND HYDROGEN GAS ACCUMULATES.
EVAPORATOR AND CONDENSOR UNITS	ELECTRIC SHORT COULD IGNITE INSULATION OR FREON AND OIL WHICH MIGHT BE PRESENT IF FREON LINES ARE RUPTURED SIMULTANEOUSLY WITH OCCURENCE OF SHORTS.
AIR COMPRESSOR	OVERHEATING SUCH AS IF POOR LUBRICATION IN UNIT COULD CAUSE IGNITION OF OIL OR OTHER ADJACENT FLAMABLE MATERIAL. SHORT CIRCUIT IN UNIT COULD CAUSE IGNITION UNDER SUCH CONDITIONS.
AIR SUSPENSION	VALVES CONTROLLING AIR PRESSURE COULD PRESENT A FIRE HAZARD IF FAULTY ELECTRIC COMPONENT IN VALVE OCCURS AND FLAMABLE MATERIAL IS PRESENT.
HIGH VOLTAGE CABLES	POSSIBILITY OF IGNITION OF FLOORING MATERIAL IS PRESENT IF CABLE ARE SHORTED TO GROUND.

SOURCE: BART VEHICLE FIRE-HARDENING PROGRAM, MARCH 1981

Table 5-2
TABULATION OF INTERIOR MATERIALS USED IN VARIOUS RAPID TRANSIT AND COMMUTER CARS

TRANSIT SYSTEM	A	B	C	D	E	F
INSIDE LINER						
SIDE	KYDEX, ROYALITE, NORYL	MELAMINE ON LAMINATED PLASTIC	ACRYLIC-POLYVINYL CHLORIDE	BALANCED MELAMINE	MELAMINE ON LAMINATED PLASTIC	MELAMINE ON ALUMINUM
SIDE CEILING	BALANCED MELAMINE	MELAMINE ON ALUMINUM	ACRYLIC-POLYVINYL CHLORIDE	BALANCED MELAMINE	MELAMINE ON ALUMINUM	MELAMINE ON ALUMINUM
CEILING CENTER	VINYL ON ALUMINUM	MELAMINE ON NOVAPLYMETAL	MELAMINE ON ALUMINUM FACED HONEYCOMB	BALANCED MELAMINE	MELAMINE ON PLYMETAL	MELAMINE ON ALUMINUM
END	MELAMINE ON PLYMETAL	MELAMINE ON PLYMETAL	ACRYLIC-POLYVINYL CHLORIDE	MELAMINE ON LAMINATED PLASTIC	MELAMINE ON PLYMETAL	MELAMINE ON ALUMINUM
INSULATION	FIBERGLASS	FIBERGLASS	FIBERGLASS	RIGID URETHANE	FOAMED URETHANE FIBERGLASS	FOAMED URETHANE
SEATS						
CUSHIONS	NEOPRENE	URETHANE	NEOPRENE	SPRINGS URETHANE	NEOPRENE	URETHANE
BACK	KYDEX ROYALITE	ROYALITE	ROYALITE	STAINLESS STEEL	KYDEX	STAINLESS STEEL

SOURCE: BART VEHICLE FIRE-HARDENING PROGRAM, MARCH 1981

Table 5-3
LINER CANDIDATE EVALUATION

DESIRED FEATURES	MATERIAL							
	POLYESTER (UNTREATED)	POLYESTER (FIRE RETARDED)	PHENOLIC (SHEET)	PHENOLIC (MOLDED)	POLYETHERIMIDE (THERMOPLASTIC)	PROTECTIVE COATING	MELAMINE ON ALUMINUM	METAL (KLAUDER)
FIRE RESISTANCE	BAD	FAIR	GOOD	GOOD	GOOD	POOR ONE SIDE ONLY	FAIR	NON-FLAMMABE
MAINTENANCE	GOOD	GOOD	GOOD	GOOD	GOOD	GOOD	GOOD	GOOD
COST/SQ. FT.:								
MATERIAL	-	$3.00	$7.00	$5.00	$10.00	DEPENDS	$1.60	$2.55
FINISHED PARTS	$3.00	5.00	8.25	10.50	12.00	ON TYPE	15.80	16.75

SOURCE: BART VEHICLE FIRE-HARDENING PROGRAM, MARCH 1981

also included in the table because of its ability to lessen the impact of fires.

[redacted]cs

Cured phenolic plastics do [redacted]y, have high thermal stability and high charring tendency in the presence of fire. Laminated phenolic planels are similar to polyester panels in appearance, weight, size, and resistance to graffiti and vandalism. They are, however, somewhat more expensive because of higher manufacturing costs.

The laminated panels are manufactured by compression mold tooling. The molded material are usually in the form of pre-impregnated laminates which are heat and pressure cured with decorative surface film to improve its appearance and enhance its maintainability. These panels are available in sheet stock with forming capabilities limited to one direction of bend. The radius of bend is dependent on the sheet thickness. Phenolic plastics may be used as interior liners.

Polyester Plastics

Materials made from polyester resins have found widespread use because of its versatility and low cost. The material, however, has poor fire resistance qualities, even when it has been modified with inorganic fillers and fire retardant chemicals. In the presence of fire, the latter produces great amounts of smoke. Polyester plastics may be used as interior liners.

Polyimide Plastics

Polyimide plastics like phenolic plastics have good fire and heat resistance qualities. Its manufacturing costs, however, are high in comparison to other plastics. In addition the material cannot be formed into large panels. Attempts by Solar Turbines International under contract with NASA, to fabricate large panels from compressed polyimide foam have failed to produce favorable results.

Other Plastics Presently in Use

In addition to polyester, other plastics such as acrylic - polyvinyl chloride and polycarbonate are used in the industry. These plastics are relatively inexpensive but have poor fire resistance. Furthermore, they are heat sensitive, that is, they tend to soften, loose their original shape and fall away from their support structure when the temperature approaches the softening temperature of the plastic. These plastics may be used for air conditioning ducts and seat pans.

Fire Retardant Coatings

There are two basic types of fire retardant coatings, intumescent and sacrificial coatings. Intumescent coatings are those which when heated swell up and form an insulative char barrier over the substrate. Sacrificial coatings on the other hand are consumed in various ways. Regardless of how the consumption takes place, the material removed carries away some of the heat energy which otherwise would have gone into the substrate.

Most coatings are either fragil or their fire retardant properties decrease with time and/or environmental exposure, thus they require periodic maintenance. In addition, coatings are heavy and thick layers are neeeded for adequate fire protection.

Metallic Materials

Panels made of aluminum and stainless steel are presently in use in the industry, of the two, steel has the better qualities because of its higher melting temperature. However, it is heavier than aluminum.

5.3 Evaluation of Vehicle Floor Materials

There are several types of composite materials being presently used by the rapid transit system. These are listed in Table 5-4. All these materials are fabricated in panels for ease of installation. Their advantages/disadvantages are discussed below.

Plymetal

There are two types of plymetal panels. Aluminum faced, and steel faced, with several types of filler material between the metal skins. The aluminum skin panels are lighter than those made of steel, however, their resistance to fire is much less than those made of steel because of their relatively low melting temperature (about $1180^{\circ}F$ or $638^{\circ}C$), which makes them vulnerable to attack by moderate undercarriage fires. Stainless steel on the other hand, melts at about $2500^{\circ}F$ ($1500^{\circ}C$) but weighs about three times as much as a sheet of aluminum of comparable dimensions.

Honeycomb

Honeycomb sandwich panels are fabricated of many different materials and combinations, and if fabricated of, and filled with, fire resistant materials, are a good fire barrier. These panels have good strength to weight ratio but are relatively expensive compared to other panel configurations, especially honeycomb panels filled with insulation material.

Table 5-4

TABULATION OF FLOOR MATERIALS USED IN VARIOUS RAPID TRANSIT AND COMMUTER CARS

TRANSIT SYSTEM	A	B	C	D	E	F
FLOOR	3/4 ALUMINUM PLYMETAL WITH HONEYCOMB CORE (3/4 IN. THICK)	3/4 IN. THICK ALUMINUM PLYMETAL	5/8 IN. THICK ALUMINUM PLYMETAL	3/4 IN. THICK PLY-WOOD W/ STAINLESS STEEL TOP FACE	3/4 IN. THICK ALUMINUM PLYMETAL	3/4 IN. THICK PLYWOOD

SOURCE: BART VEHICLE FIRE-HARDENING PROGRAM, MARCH 1981

Balsa Core Sandwich

Balsa wood is a good fire retardant. It is light in weight and when used with a metallic substance has acceptable load bearing ability.

5.4 Countermeasures to Prevent and Control Fires

A major consideration in preventing fires is to develop high resistance to fire penetration in the floors, sidewalls, and roof. It should be noted that for fire to occur, there must be an ignition source, as well as combustible material and air to sustain the fire. The absence of any of these elements insures that fire will not occur. Obviously, it is not possible to design a vehicle which is completly ignition proof, as these three elements will to some extent, always be present. However, it is possible to minimize the risk of starting fires by reducing the amount of flammable material available to fuel a fire.

5.4.1 Undercar Fires

As stated before, undercar fires can involve the vehicle's floor and/or walls. However, before the wall material is ignited, the juncture between the wall and the floor must be breached. This is not particularly difficult to accomplish since air conditioning ducts, and electrical cables extend from beneath the car into the sidewalls. Thus to prevent fires from spreading through the walls, in addition to the use of sidewall liners which are resistant to fire, the juncture should be filled with fire resistant material. One such material is silicone foam. This material is used as fire blocking in cable penetration of building construction and nuclear plants. Under fire conditions, the foam tends to char and resist fire penetration.

In order to prevent the vehicle's floor from being breached, two approaches may be followed, the areas which are most susceptible to fires may be protected with fire resistant coating, or the floor may be built of fire resistant material. The only two materials that would not ignite are aluminum and stainless steel. However, both are good conductors of heat, so that the material used as filler in these panels can be ignited if the temperature is high enough, thus it is recommended that the filler material used in these panels have good thermal properties.

5.4.2 Interior Fires

In order to minimize the occurrence and impact of interior fires, the vehicles should be cleaned frequently to avoid the accumulation of flammable material, system's patrons should be discouraged from leaving newspapers and other paper material behind when they leave the train or discouraged from carrying flammable material aboard. In addition, seat and wall liners should be fabricated of fire resistant material. Carpets should be made of, or treated with, fire retardant chemicals.

5.4.3 Response to Fires

Because rapid transit systems operate through many localities, each with its own fire department, the transit property should insure that the different departments have cooperation agreements, so that in case of fire at the boundary line separating two localities, there would not be any confusion concerning who is to respond.

Finally, in order to minimize the response time from fire detection to response by the fire department, the operations control center should have a clearly delineated fire operations procedure indicating what fire department is primarily responsible for answering to the scene of fire in a given area, and what department is to answer in case the first one cannot. All fire department and central control personnel should be thoroughly trained in these fire emergency procedures.

6.0 EMERGENCY EGRESS

Emergency egress is the evacuation of passengers from a disabled train, in a manner that does not lend itself to injury to the passengers. Emergency egress procedures are called for during collisions, derailments, fires, and flood conditions which leave the train unable to operate and which may result in injury to the passenger. In the next sections, the emergency egress procedures for BART, and WMATA are examined, system interdependencies are identified and the effect of these interdependencies on the overall effectiveness and reliability of the system will be investigated. Passenger initiative (system independent) options will be investigated to assess its advantages/disadvantages.*

6.1 Operational Emergency Egress Procedures

The different systems analyzed in this report respond to emergency egress condition in different ways, these vary from decision and immediate action by the operator, to decision and action by central control. The procedure followed by the different systems is outlined below.

6.1.1 BART Emergency Egress Procedure

The BART emergency egress procedure distinguishes and provides guidelines for two different types of situation: those which are of no immediate danger to the systems patrons, and those which represent an immediate threat. In the first case, for the purpose of letting the passengers off at locations which they are familiar with, the evacuation is to be carried out at sites other than the site of the incident. The

* UMTA is in the process of developing guidelines for emergency egress procedures.

new site is to be selected, jointly by the train operator and Central Control, after an evaluation of the train's movement capability, location and load, has been made. In order of desirability, these are:

- Stations
- Maintenance-of-way access point
- Trackage at grade
- Aerial structures
- Underground (between stations).

Train operators are prohibited from trying to reach a station if there is a fire on board, and the train has to enter the underground to reach it. In addition, if the disabled train is in an underground area, the first action the operator should take is to try to get the train moving again. If this fails, the operator is instructed to attempt to proceed with a fraction of the consist, if it is possible to accomodate all the passengers. In the second case, egress is to take place immediately.

Egress at sites other than at stations, proceed after Central Control confirms that the third rail power has been removed from under the affected train, and in accordance with procedures appropriate for the train location and condition. Once this is done, rescue trains evacuate the passengers to a safer area.

The BART emergency evacuation procedures vary for ground level, elevated structure, subway, Transbay or Berkeley Hills Tunnel. In all instances, however, the passengers are advised and assisted by the operator. During peak travel periods, an additional BART employee is present in the train for the routes utilizing the transbay tube, and the Berkeley Hills tunnnel. In addition, there are signs instructing the passengers what to do, and where to go in an emergency situation.

6.1.2 WMATA Emergency Egress Procedure

WMATA's emergency egress procedures like BART's distinguishes and provide guidelines for those situations which do not threaten the passengers safety, and for those that do. In the first case, the train operator is advised by Operations Control Center to uncouple the disabled car(s) transfer the passengers to the other car(s) and proceed to the nearest station. If this cannot be accomplished, a rescue train evacuates the passengers.

If it is necessary to evacuate the passengers to the right-of-way, WMATA requires that, before the evacuation takes place, circuit breakers be physically removed from the circuit breaker panel to deactivate the third rail, and that representatives from different WMATA departments as well as Fire and Police departments be present to assist in the evacuation of the passengers.

In the WMATA system, passengers are unaware of exit locations, or of manual procedures for opening train doors, etc. In general, very little information concerning emergency egress pocedures is available to the public.

6.2 Conclusions and Recommendations

The most striking difference in the emergency egress procedure for the two transit systems discussed in this report, is the level of passenger involvement permitted. BART has provisions for it, WMATA does not. The former by providing information on the location and operation of the emergency door releases, the perils associated with the third rail, and directions to doors connecting opposite track ways, insures that even in the event the train operator is disabled the passengers will still be able to see themselves out of danger. The latter, by requiring the presence of Fire and Police personnel in addition to its own personnel in the incident area, insures that the evacuation will be carried out in the safest manner.

However, there are instances when it is necessary to evacuate the train without delay. One such instance is, for example, the eruption of a massive fire in the consist. Such an event would be disastrous in a system operating like WMATA. In these panic conditions, when everybody is trying to get out and away from the train, communicating instructions to hundreds of persons would be a difficult task, specially when there is only one person to accomplish it. The situation becomes even worse if the train intercommunication system, or the operator, is disabled. In the former case there would not be any instructions issued to the passengers. In the latter case, the passengers would be trapped until the doors could be forced open. And once they are open, the passengers are not aware of the dangers posed by the third rail or the shoe collectors. In a scenario such as this, there would be copious amounts of heat, or smoke, or both. If the fire occurs in an underground section of the track, it becomes imperative to move into a sheltered area, such as the opposite track way. For a system such as the one described here, finding the nearest access door would be quite a task as there are no instructions indicating the location of these doors.

Thus it is recommended that for the purpose of facilitating evacuation of passengers in emergency conditions, a emergency egress plan similar to the one in effect at BART be adopted.

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APPENDIX A

OVERTURNING MOMENTS

Figure A-1 shows an schematic diagram of the overturning moments due to the wind load F and the vehicle weight W about point B. The moment, M_F, due to the wind load is:

$$M_F = F \cdot h/2$$

The moment, M_w, due to the vehicle weight is:

$$M_w = W \cdot d/2$$

Then for overturning to occure, $M_F > M_w$.

If the vehicle is negotiating a horizontal curve, the forces acting on the vehicle are as shown in Figure A-2, where in addition to the wind load F, and the vehicle weight W, there is an additional force, the centrifugal force, C, due to the circular motion of the vehicle.

The moment, M_1, due to the wind load and the centrifugal force, around B is:

$$M_1 = F \cdot \frac{h}{2} + \frac{Wv^2}{gR} \cdot \frac{h}{2} \cdot \frac{\cos(\alpha+\beta)}{\cos\beta}$$

The moment due to the vehicle weight W, is:

$$M_w = W \cdot \frac{h}{2} \cdot \frac{\sin(\alpha+\beta)}{\cos\beta}$$

However, since the vehicle is slightly inclined due to the super elevation of the track, there is also an additional moment $M_{F'}$, due to the wind load on the roof of the car. This moment is:

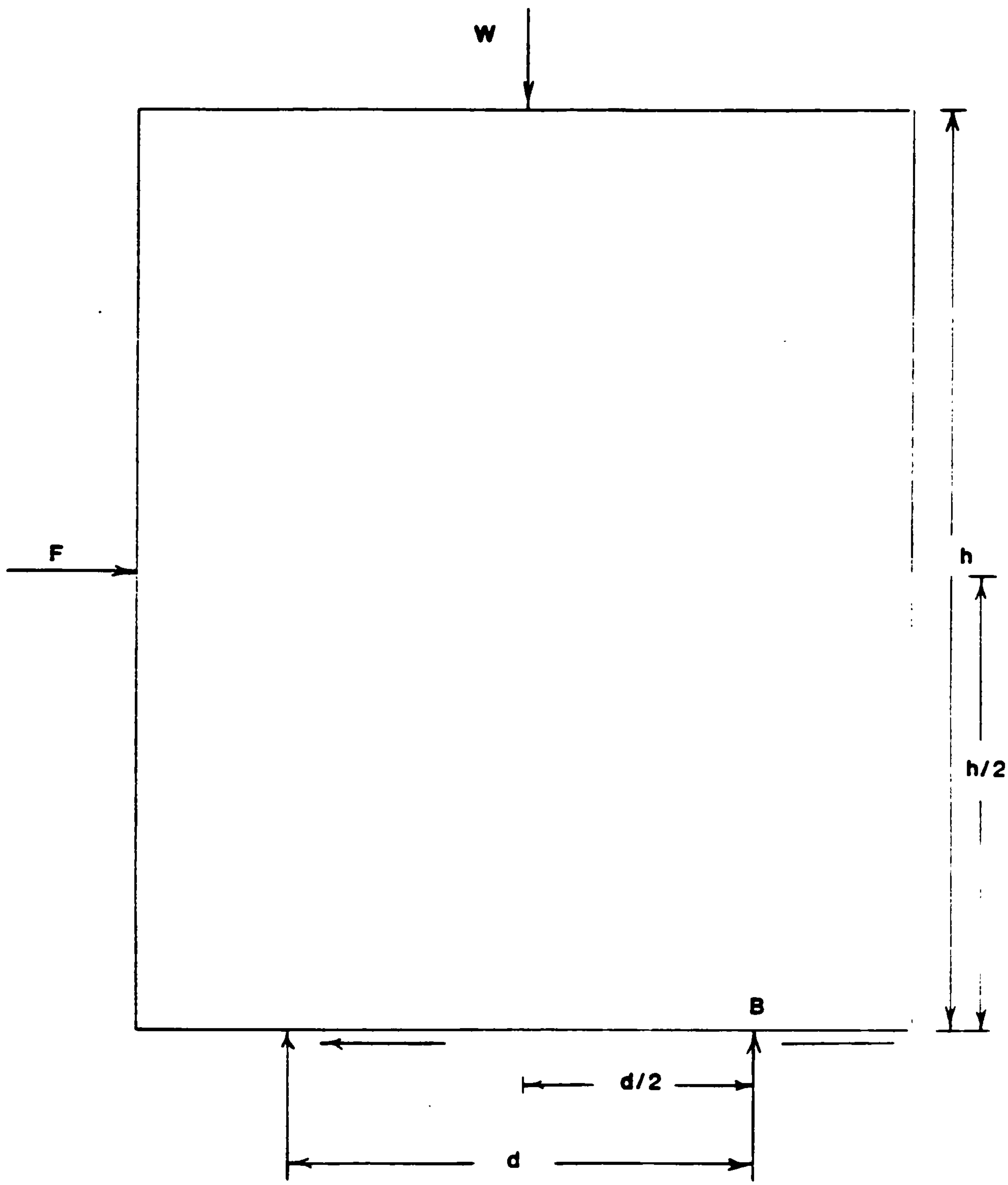

Figure A-1 Overturning Moments Horizontal Track

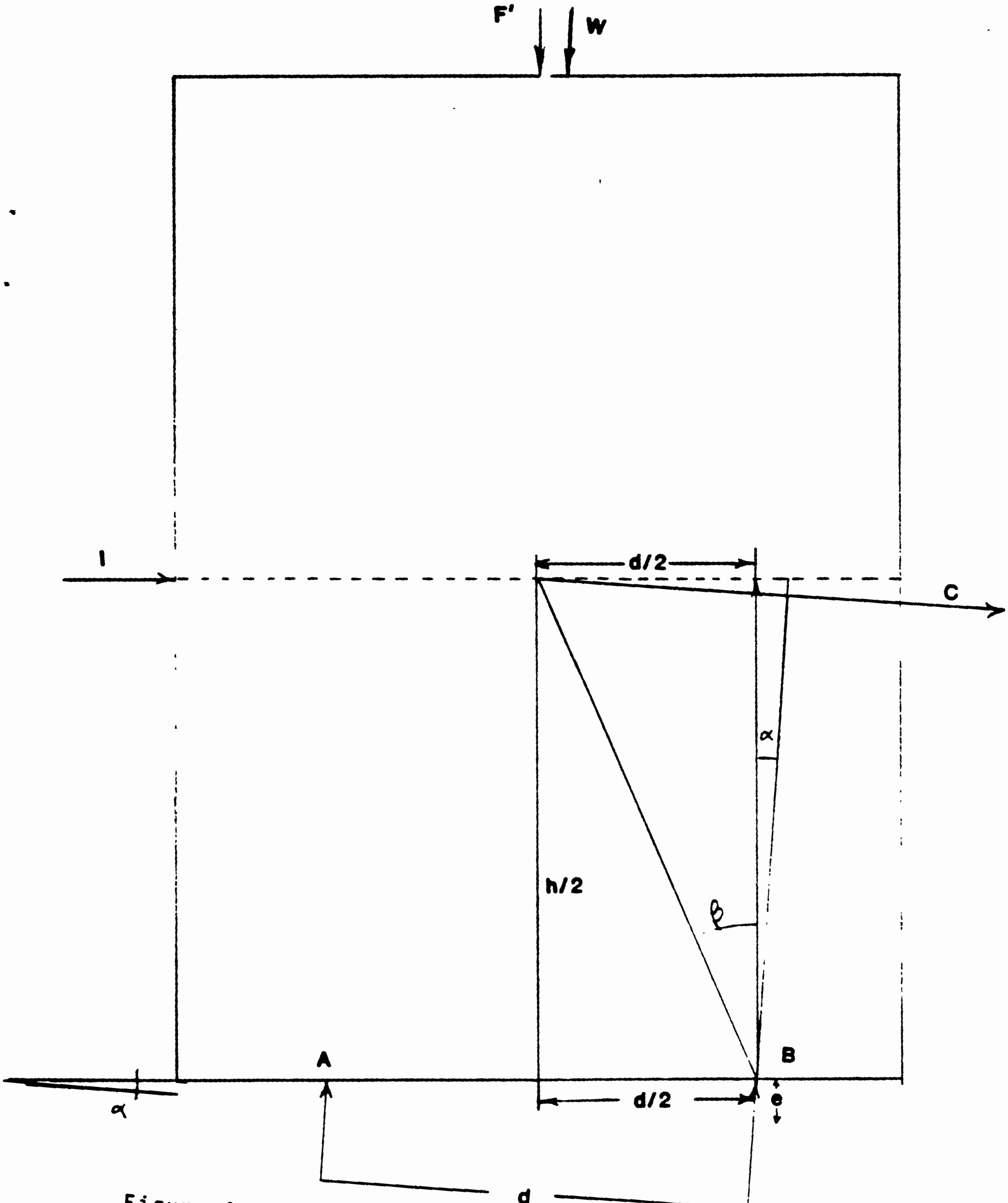

Figure A-2 Overturning Moments Horizontal Curve

$$M_{F'} = F' \cdot d/2$$

Thus, the moment opposing that of the wind is the sum of these two:

$$M_W + M_{F'} = W \cdot \frac{h}{2} \cdot \frac{\sin(\alpha + \beta)}{\cos\beta} + F'\frac{d}{2}$$

APPENDIX B

STOPPING DISTANCES

The forces acting on a moving car are as shown in Figure B-1. The work done in stopping a moving car must be equal to its kinetic energy. Thus,

$$\frac{1}{2} mv^2 = \int_0^S F ds$$

$$\frac{1}{2} \cdot \frac{W}{g} \cdot v^2 = \mu W \int_0^S ds$$

performing the integration, and rearranging terms:

$$S = \frac{v^2}{2g\mu}$$

where

S = stopping distance

μ = adhesion coefficient

g = gravity constant

v = velocity

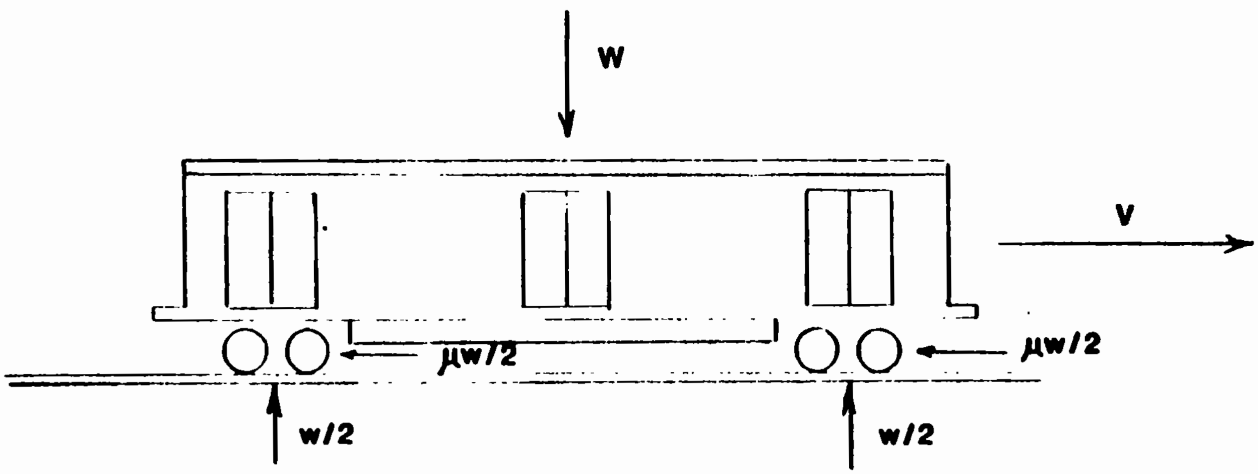

Figure B-1 Schematic Diagram of Forces Acting on a Moving Vehicle

APPENDIX C

ANALYSIS OF LIGHTNING

Since lightning is an electrical discharge of short duration it may be considered, for purposes of analysis, to be an impulse function in the sense of Electrical Engineering theory. Such a function may be represented graphically as shown in figure C-1, and mathematically as shown in the equation:

$$M = \lim_{\varepsilon \to 0} \int_{t_1}^{t_2} \delta(t)\, dt \tag{1}$$

where $\delta(t)$ is the "delta function" which has a value only at time t_0, that is when lightning occurs, otherwise its value is zero at all other times. In addition the delta function is a function of the impulse duration, ε, of all the electromagnetic radiation that resulted from the discharge. The result of the integration yields M, which contains a sequence of multiples of $1/\varepsilon$, that is ε as the denominators. At the limit, as ε approaches zero, or as t_2 and t_1 approach t_0, the value of M becomes infinite.

The frequency distribution of M is obtained by performing a Fourier Transform of equation (1). This is:

$$\beta = \int_{-\infty}^{+\infty} \delta(t)\; e^{-j\omega t}\, dt \tag{2}$$

where the different β 's are the amplitude coefficients of the different harmonics. Plotting the results of equation (2) results in the graph shown in Figure C-2. From the figure, it can be seen that there is little or no sustained frequency effect either by amplitude or by specific harmonics. From equation (1), the maximum impact of lightning comes at the time when the lightning occurs. Theoretically, this impact would be of infinite magnitude, however, its effect is neutralized by proper grounding.

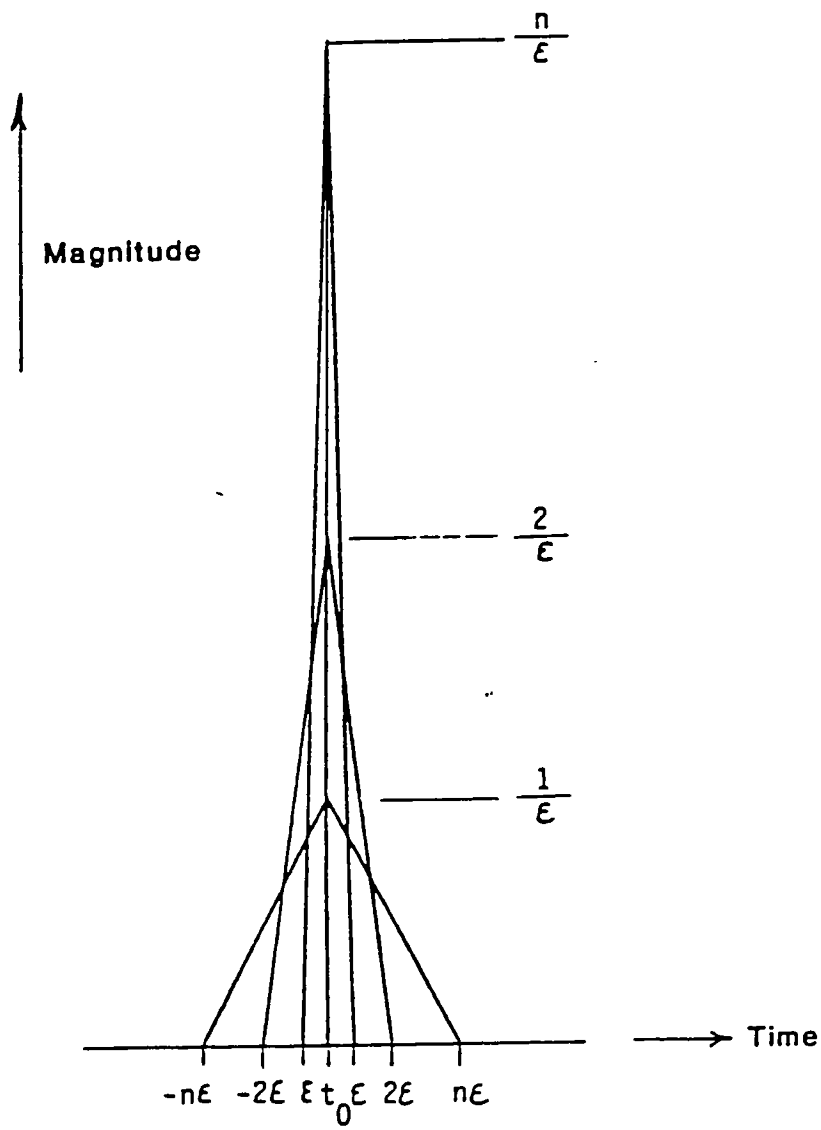

Figure C-1 CHARACTERISTICS OF THE IMPULSE FUNCTION

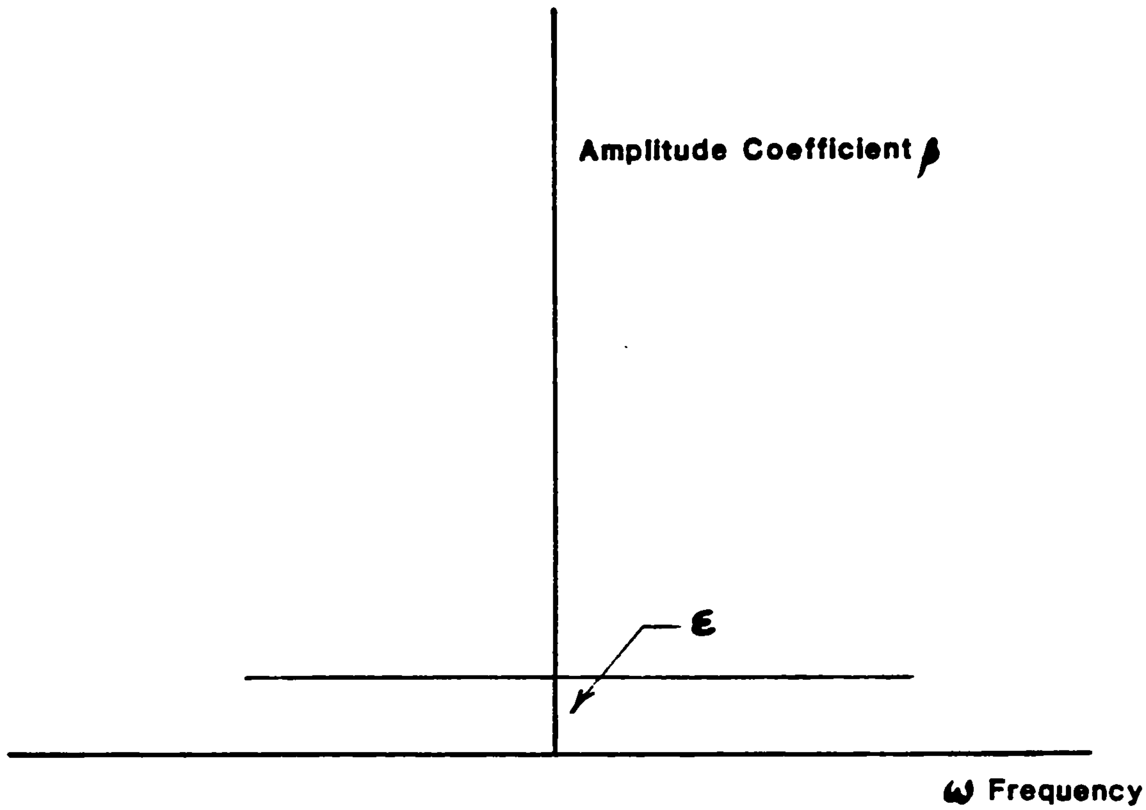

Figure C-2 IMPULSE FUNCTION FREQUENCY DISTRIBUTION