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SAFETY AND AUTOMATIC TRAIN CONTROL FOR RAIL RAPID TRANSIT SYSTEMS

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16. Abstract

The anticipated construction and expansion of rail rapid transit systems in the United States over the next 10-15 years implies major capital expenditures. A significant level of automation in train control is likely to be central to these systems. The potential safety problems associated with various implementation alternatives, several possible levels of automation, and uncertainty in the corresponding proper role of the human operator raise issues requiring timely resolution. This report describes the state-of-the-art in rail rapid transit system automatic train control, assesses the safety related interrelations between the train control system, functions of the human operator and other portions of the total system, and makes recommendations, based on current experience, to aid the process of planning, funding approval, design, implementation, test, safety certification and operation of new systems or modifications of existing systems. The Study suggests that the Federal Government develop safety criteria by which to evaluate future proposals and establish guidelines for safety certification procedures. It also concludes that knowledgeable application of system engineering skills and advanced development program techniques together as a process, are probably more important to achieving a successful new rail rapid transit system than are individual design decisions or application of advanced technology.

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EXECUTIVE SUMMARY

This document is the result of a study by the Department of Transportation's Transportation Systems Center, on the safety-related problems in the automation of rail rapid transit control systems. It was conducted under the auspices of the Department of Transportation, Assistant Secretary for Environment, Safety and Consumer Affairs and funded by the Federal Railroad Administration and the Urban Mass Transportation Administration.

The objectives of the Study were to:

1. Describe the state-of-the-art in automatic train control for rail rapid transit systems.
2. Assess the safety-related interactions between the design of the automatic train control system, functions of the human operator and other portions of the total transit system.
3. Make recommendations that would aid the processes of planning, funding approval, design, implementation, test and operation of new systems or modifications of existing systems.

The initial line of inquiry of the Study was to survey existing and proposed rail rapid transit properties exemplified by the following spectrum:

- Well established systems which have added or plan to add new lines or new equipment using higher levels of technology than on their older lines are examplified by lines of the Chicago Transit Authority (CTA), London Transport, Regie Autonome Des Transports Parisiens (RATP) in Paris, the New York City Transit Authority (NYCTA), and the Massachusetts Bay Transportation Authority (MBTA) in Boston.
- Contemporary examples of fully operational, modern rail rapid transit systems are the Port Authority Transit

Corporation (PATCO) Lindenwold Line in Philadelphia and the Sistema de Transporte Colectivo (STC) in Mexico City.

- A modern system planned for a region where no major rail rapid transit system previously existed in exemplified by the Bay Area Rapid Transit (BART) System of the San Francisco area, partially operational since 1972.
- A system now under construction is typified by the Washington Metropolitan Area Transit Authority (WMATA).
- Systems still in planning stages have been proposed for Atlanta, Baltimore, and Buffalo.

Such rail rapid transit systems are facing increasingly greater operational demands. During the last several years, in order to attract and maintain ridership, these systems have striven to offer convenient, dependable, comfortable, economical and safe service. In view of the current energy crisis, significant increases in passenger demand may be imminent. These greater demands represent requirements for improved vehicle performance and traffic control, and have resulted in a trend toward increased train control system automation. The Table in this Summary summarizes the rather extensive degree of train control system automation existing in a portion of today's rail rapid transit systems.

The anticipated construction and expansion of rail rapid transit systems in the United States over the next 10-15 years implies major capital expenditures. The Federal Government, through the Capital Assistance Program of the Urban Mass Transportation Administration of the Department of Transportation, will be asked to provide the major share of these funds. Thus, it is important for the Federal Government to develop safety criteria by which to evaluate proposals and establish guidelines for safety certification procedures. It is intended that this report aid this process with respect to various levels of automation and their impact on safety.

A significant level of automation in train control is central to all new and planned rail transit lines. The effects on safety of various automation level possibilities and of the selected

DEGREE OF TRAIN CONTROL SYSTEM AUTOMATION EMPLOYED BY A SAMPLE OF TRANSIT AUTHORITIES

Most Automated Line of Transit Authority	Degree of Train Control System Automation (Operational or Intended)
Bay Area Rapid Transit District (BARTD) All lines	Fully automatic train control system. No on-board operator required to perform all normal train operations including starting, stopping, door control and speed command tracking. Train attendant in cab enhances safety and operations through visual surveillance. Train attendant can run train manually in non-normal situations only at reduced speeds. Extensive use of computers for centralized automatic train supervision. Train supervision in non-normal situations is manual.
Chicago Transit Authority (CTA) Lake-Dan Ryan Line	Automatic cab control signalling. On-board operator required to start train by placing controller in maximum speed position. Train automatically accelerates and tracks maximum allowable speed. Manual braking for station stops. Conductor required for door operations. In non-normal situations the operator can run the train manually at maximum allowable speeds. Manual monitoring of operations in response to preprogrammed automatic scheduler at central control.
London Transport Victoria Line	Functionally equivalent to BARTD entry above except: 1. Operator required to open doors, close doors, and start train after each station stop. 2. In non-normal situations the operator can run the train manually at maximum allowable speeds.
Massachusetts Bay Transportation Authority (MBTA) Red Line	Functionally equivalent to CTA entry above.

DEGREE OF TRAIN CONTROL SYSTEM AUTOMATION EMPLOYED BY A SAMPLE OF TRANSIT AUTHORITIES - CONTINUED

Most Automated Line of Transit Authority	Degree of Train Control System Automation (Operational or Intended)
New York City Transit Authority (NYCTA) Second Avenue Line, under construction	Automatic cab control signalling. On-board operator required to push "GO" button. Train automatically accelerates and tracks maximum speed. Automatic deceleration for programmed station stops. Conductor required for door operations. (Operator can control doors.) In non-normal situations, the operator can run the train manually at maximum allowable speeds or at restricted speeds, depending upon the situation.
Port Authority Transit Corportation (PATCO) Lindenwold line	Functionally equivalent to BARTD entry above except: 1. Operator required to perform door operations and start train after each station stop. 2. In non-normal situations the operator can run the train manually at maximum allowable speeds. 3. Manual monitoring of operations at central control in response to automatically obtained surveillance information. No extensive computers.
Regie Autonome Des Transports Parisiens (RATP), Paris Line#1, #4, and #11 (#6 in process of conversion)	Functionally equivalent to BARTD entry above except: 1. Operator required to close doors and start train after each station stop with single button. 2. In non-normal situations the operator can run the train manually at maximum allowable speeds.
Sistema de Transporte Colectivo (STC) Mexico City Line #1, #2 and #3	Automatic cab control signalling. On-board operator required to manually control train within speed limit commands. Manual braking for station stops. Operator in cab performs door operations. Central control performs computer assisted dispatch, tracking, spacing, and log of train operations. (Plan conversion to fully automatic train operation including dispatch, starting, stopping, door control, and speed command tracking.)
Washington Metropolitan Area Transit Authority (WMATA) Under construction	Functionally equivalent to BARTD entry above

Note: Each system listed above has a fully automatic train protection system.

role of the human operator in a system are many and, in general, not clearly understood. This Study focused on the relationship between automatic train control and safety in rail rapid transit systems because safety is of paramount importance in systems transporting large numbers of people. Safety permeates the total system design process including station design, rail and right-of-way specification, vehicle design, man-machine interfaces, operational procedures, personnel training, and motivation of people. In addition, the train control system performance, reliability and maintainability, necessary for high levels of passenger service and overall operational availability of the transit system, are almost of equal importance, which leads to conflicts.

Other aspects of automatic train control such as cost and operational flexibility were considered in the Study even though the principal concern was safety. The conclusions point out the strong interrelations among such factors and safety, and the need for considering all of them in any decision concerning the use of automatic train control.

One of the main problems in designing train control systems is the influence of safety requirements on the design. During the course of the Study it was concluded that no general safety design criteria exist from which quantitative equipment specifications and operating procedures could be derived for train control system design purposes. Fail-safe design was the only common principle found in extensive use. Although a very useful building block, applicable on a component-by-component or single function basis, the fail-safe criterion was found to be inadequate by itself. Although safe, halting a train and perhaps the entire system until a failure can be repaired is operationally unacceptable in a high density short headway system. Manual intervention procedures to compensate for such failures and to continue operations are generally not fail-safe of themselves. A much higher form of overall system safety criteria is required to govern procedure in these and various other non-normal situations.

The National Transportation Safety Board in a recent study recommended abandonment of "the concept of fail-safe design for rail rapid transit systems in favor of modern, effective system safety management and safety analysis methods."*(1) Such a major step would have to be taken with great care, and it would be important to provide the mechanism for such a change. The problems of reliability, safety, operational requirements, and maintenance could then be attacked simultaneously with advanced system analysis techniques and design methods, including fail-safe components, fail-operational subsystems, redundant subsystems, and hierarchical control. Most importantly, the ability to incorporate appropriate new technology in rail rapid transit systems would be greatly facilitated.

Summary conclusions and recommendations are given below. Discussion of these findings are given in Section 8 of the Report and, to a lesser degree, elsewhere in the Report.

Summary of Conclusions

1. Adequate safety criteria or standards for rail rapid transit systems by which automatic control system design may be quantitatively assessed with respect to safety requirements are not available.
2. The concept of "fail-safe" design is inadequate by itself to specify the safety requirements for rail rapid transit automatic control systems.
3. The automatic train protection subsystem, which is a major part of automatic train control, is in general use, well proven, and should continue to be automated.
4. More development work is required to support fully-automated, high density, short headway systems by making train surveillance systems more continuous, more reliable, and more independent of track layout and changing local track environment.
5. In future rapid transit systems, a human operator will be required as part of the surveillance

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*References are given in Appendix F.

function unless a much higher level of exclusive right-of-way protection than has been currently achieved, can be provided.

6. Train operation systems have been implemented lacking any clear basis for determining the optimum level of automation as a function of system requirements. Any one of several levels of train operation automation from fully manual to fully automated speed control may be justified depending on criteria over and above technical feasibility, such as cost and desired service levels.

7. The train operator function should be designed with special attention to maintaining acceptable levels of vigilance and motivation. There should be appropriate operating, safety, emergency, and surveillance tasks to enhance alertness; a properly designed cab; and initial and refresher training to optimize the operator's performance.

8. The initial capital cost of an automatic train control system for a new rail rapid transit system is typically only three or four percent of the total initial system cost. Yet, a much larger percentage of initial planning, design effort, and management attention should be appropriated to development of the automatic train control system in proportion to its impact, which is major, on overall system safety, quality of service, and recurring operational and maintenance costs.

9. Pertinent system design, test, evaluation and management methodologies and experience from other fields of modern technology have not been fully utilized in the design and implementation of new rail rapid transit systems. The complicated process of new system specification, introduction of new technology, source selection, contract management, systems integration, first article testing,

systems testing, rework prior to approval for revenue service and continued rework to achieve reliability and maintainability goals can be significantly improved for future systems relative to recent experiences with this total process.

Summary of Recommendations

1. National rail rapid transit safety standards and guidelines should be developed by intergovernmental efforts in cooperation with the transit properties, manufacturers, and suppliers to form the basis for a safety certification process for new systems. As the first steps toward this goal:
    a. Existing rail rapid transit accident and incident data collecting processes must be unified and upgraded to support the development of safety criteria allowing safety assessment of present and proposed systems.
    b. Safety criteria, standards, and procedures which allow assessment of the design of train control systems with respect to safety requirements should be developed for rail transit systems. Specifically, the concept of fail-safe design should be only a building block within the larger framework of an overall system safety assurance program plan tailored to each new system.
2. Appropriate system safety analysis and automatic train control expertise should be an integral part of the early system planning and design process.
3. More stringent and better monitored contract management, test programs, and rework mechanisms should be developed by transit authorities to verify contractor adherence to the automatic train control system safety, operational and reliability standards specified. Evidence of such contract management philosophy and the corresponding

needed technical staff capabilities should be required of a property as part of any federal or other public funding support process.

4. Automatic train control system development efforts should be supported in the areas of
   a. Train surveillance subsystems with increased continuity and reliability.
   b. Total system safety design (including the train cab and central control) for optimum balance between automation alone and automation with human enhancement.
   c. Train supervision functions including hierarchical computer control and optimization of scheduling.
   d. Operational, maintenance, and reliability characteristics of alternative automatic train control system implementations.
   e. Alternate means to cope with subsystem failures other than simply stopping the trains.
5. The decision on the presence and function of the on-board human operator should be based on careful analysis of the particular requirements of each new rail rapid transit system. Particular attention should be given to the requirements of
   a. Right-of-way protection and track surveillance.
   b. Door monitoring at stations.
   c. Vehicle and passenger safety and security.
   d. Emergency assistance and control.
   e. Cost/benefit of implementing various levels of automation.
   f. User acceptability.

PREFACE

This study was initiated and conducted under the direction of Dr. Robert E. Gilruth of the NASA, Johnson Space Center. Dr. R. Eugene Goodson contributed substantially to the early stages of the study effort while a consultant to the DOT Transportation Systems Center. NASA AMES Research Center personnel made significant contribution to track circuit testing efforts done in cooperation with the Bay Area Rapid Transit District. These various contributions to the study effort are hereby gratefully acknowledged.

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1. INTRODUCTION

This document is the result of a study by the U.S. Department of Transportation's Transportation Systems Center of the safety-related problems in the automation of rail rapid transit control systems. It was conducted under the auspices of the Department of Transportation Assistant Secretary for Environment, Safety and Consumer Affairs and funded by the Federal Railroad Administration and the Urban Mass Transportation Administration.

The purpose of this report is to describe the state-of-the-art in automatic train control of rail rapid transit systems, to assess the safety-related interaction between the automatic control system and other portions of the total system, and make recommendations based on current experience that will aid the process of planning, funding approval, design, implementation, test, and operation of new systems or modification of existing systems.

Current and planned rail rapid transit systems are facing increasingly greater operational demands. During the last several years, in order to attract and maintain ridership, these systems have striven to offer convenient, dependable, comfortable, economical, and safe service. In view of the current energy crisis, significant increases in passenger demand may be imminent. These greater demands represent requirements for improved vehicle performance and traffic control, resulting in a trend toward increased levels of train control system automation. Existing rail rapid transit systems are, in general, considering only the addition of automatic train operation as an improvement to the control system, since with very limited exception, the train protection subsystems are already universally automated. New systems, in general, will incorporate the full automation of all control functions--train protection, train operation, train supervision, and communications.

An important question arising from the implementation of fully-automatic train control is, can a fully-automatic system achieve and maintain the safety levels experienced to date in the rail rapid transit industry? A primary objective of this Study, was to determine the capabilities and limitations affecting safe operations of rail rapid transit systems, arising from the employment of fully-automatic train control. This aspect of the Study was intended to be limited to those safety problems that are part of or under the jurisdiction of the train control system. This includes the functions of train protection, train operation, train supervision, and communications. Other safety considerations such as fire and security were only considered as they might interact with the train control system in a peripheral sense. There are other aspects of automatic train control such as cost, reliability and operating flexibility which have to be considered even when the principal area of concern is safety. These aspects, however, were only included in the study as required for continuity of understanding. Some of the conclusions point out the strong interrelations among these factors and safety, and the need for considering all of them in any decisions on the use of automatic train control.

A corollary objective of the Study was to identify any special safety problems arising from greater application of automation. This and allied objectives encompass such factors as consideration of industry design practices, demonstration and testing of safety systems, and characteristics or requirements of individual systems. Study recommendations were made in this area and were intended to aid in the development of new systems.

The report is organized to provide a description of the state-of-the-art in automatic train control and to assess the safety-related interaction between the design of the automatic train control system and other portions of the system. To this end, functional descriptions of a representative rail rapid transit system and its automatic train control system consisting of train protection, train operation, train supervision, and communications subsystems are given in Sections 2 and 3 respectively. A detailed review was made of a number of rail rapid transit systems representing various levels of automated train control systems. Field tests were made to enhance understanding of surveillance system characteristics. Section 4 compares the train control system characteristics of transit systems reviewed, relative to the subsystem functions and terminology of Section 3. Appendix A is an expanded tabulation of these characteristics including comparison of other features such as vehicles, track, and stations.

Particular attention was given to the role of the attendant or train operator in the Study. Section 5 describes functional roles of the train operator towards a fuller understanding of some of the safety related problems introduced in Section 4.

Section 6 and 7 build on previous chapters by suggesting new and improved design goals together with implementation and test methodology possibilities which could benefit the development of new rail rapid transit systems or the modification of existing ones. The material presented in these two sections is intended only as examples of future system designs.

Section 8 is a compilation of conclusions and recommendations followed by supporting discussion to supplement treatment elsewhere in the Report. Specific suggestions are made for further work. The report also includes technical appendices.

2. SYSTEM FUNCTIONAL DESCRIPTION AND OPERATIONAL REQUIREMENTS

2.1 GENERAL DESCRIPTION OF A RAIL RAPID TRANSIT SYSTEM

All rail rapid transit systems reviewed as part of this study and described in Appendix A contained the same basic functions and were comprised of the same basic elements. For illustrative purposes, a hypothetical system will be described to typify the common denominator of existing systems. Such a system would most likely consist of a single, relatively straight line of double track with vehicles running on an exclusive right-of-way from a generally suburban area to a downtown area, providing transportation between a series of stations along the route. The basic elements of such a system are the track network, vehicles, stations, control system and personnel.

2.1.1 Track Network

The Track Network generally has the following characteristics:

a. Two parallel main line tracks to allow independent and simultaneous train movements in opposite directions.

b. Exclusive right-of-way below ground, at grade, or on elevated structure.

c. Sufficient crossovers, storage tracks, and passing tracks to allow storage of extra or disabled trains, or maintenance on one track while the other main line track is used for revenue service.

d. Sufficient switches and yard tracks to store vehicles in off hours, assemble trains for dispatch to revenue service, and provide access to vehicle maintenance facilities.

e. Ability to report the position of switches and set switches in accordance with commands from the control system.

f. Safe civil engineering design consistent with high train speed operations with sufficient guard rails and other means to prevent encroachment of the exclusive right-of-way by people, animals, or other vehicles.

g. Distribution of electric power in response to command from the control system.

2.1.2 Vehicles

The vehicles generally have the following basic characteristics:

a. Provide seats and standing room in a safe, environmentally controlled compartment with adequate doors for access and egress at stations or for evacuation under emergency conditions.

b. Single vehicles can be coupled together to form multi-vehicle trains.

c. The ability to provide critical data such as vehicle identity, position, velocity, and status to the control system.

d. The ability to receive, acknowledge and respond to commands from the control system with regard to accelerating, maintaining constant velocity, decelerating, stopping at particular places, opening and closing doors and including options for different levels of vehicle performance such as emergency braking with higher deceleration than service braking.

2.1.3 Stations

Stations generally have the following basic characteristics:

a. Suitably spaced along the track network and sized in proportion to anticipated passenger demand.

b. Designed to provide fare collection, passenger information services, adequate space, and conveyance for rapid access to and egress from the longest trains to be operated on the track network.

c. Provide nearby parking for cars and bikes of passengers and transit system personnel.

d. House decentralized equipment of the control system.

2.1.4 Control System

The control system generally has the following basic characteristics:

a. Ability to acquire critical data such as identity, position, velocity, and operational status from every vehicle in the system at all times.

b. Ability to design and update a safe schedule of train makeup and movement in proportion to passenger demands, the critical data listed in (a) above, and any abnormal situations.

c. Ability to determine and transmit commands to the trains, and track network (switches and power) necessary to safely accomplish the schedule and cope with abnormal situations.

d. Ability to determine and transmit information on station stops, route, destination, and special circumstance data to the trains and stations for passenger information service.

e. Ability to provide communications between all transit system personnel and to provide all necessary personnel/machine interfaces with the track network, vehicle, station and control system elements of the total system.

2.1.5 Personnel

Rapid rail transit system personnel generally perform the following functions:

a. Overall system management and control.

b. Train operation.

c. Maintenance.

d. Station manning.

e. Security.

In actuality, in-being rail rapid transit systems are typically more complicated than the hypothetical common denominator two track system functionally described above but the example can be used as the basic building block to understand the more complicated systems.

The Port Authority Transit Corporation (PATCO) Lindenwold line, in Philadelphia, is an example of the simplest two track system defined above. The next more complicated situation is exemplified by the Baltimore Region Rapid Transit System which is currently planning two independent two-track lines which intersect at a common two level station. As the system grows, these lines will be extended and others will be built but each can be operated as an independent two track line. As another example, the Massachusetts Bay Transportation Authority of Boston basically has four different dual-track independent lines and a wide variety of vehicles. The lines intersect each other at dual level stations in downtown Boston. Passengers can go between any pair of stations in the system by changing trains at the appropriate intersection points.

Any crossover in the two-track common denominator system described above requires treatment of diverging and merging trains at track switches. Three track and four track main line rail rapid transit systems are basic extensions of the simple two-track system by more extensive use of track switches. The three track system gives the flexibility of running extra or express trains in the primary commuter direction of travel, which changes between the morning and evening rush hours. The New York City Transit Authority (NYCTA) has a very complicated track network with over 240 route miles of three and four track routes with numerous merge points, but the various lines still operate relatively independently of each other and can be looked at as basic building blocks.

The Bay Area Rapid Transit System of San Francisco is somewhat different from the previous examples. It has basically four different two-track lines, but three of these converge at the Oakland Wye to use the same two track Transbay Tube to downtown San Francisco. This is a divergence from the classical approach of requiring people to transfer trains at dual level stations.

It is strongly felt after reviewing these various example systems that thorough understanding of the common denominator two track system presented earlier can easily be extended by superposition to treat the complexity of any future rail rapid transit system.

2.2 OPERATIONAL REQUIREMENTS

Corresponding to the functional description of a typical rail rapid transit system, logically there must be a set of metropolitan area-particular operational requirements. The following is a reasonably consistent, typical set of such requirements.

In general, the objectives of the overall rail rapid transit system are to minimize travel time, and to provide regular scheduled service together with a high level of passenger comfort, convenience, and safety. The train control system is designed with the objectives of providing the highest practicable levels of efficiency of operation, safety to people and property, and service to patrons. The system generally employs electrically powered vehicles providing service at 90 second intervals (or less) during peak demand periods and extending to as long as 20 minute intervals (or greater) during the low demand periods. Through the use of crossovers and control of trains against the normal traffic direction, maintenance work on the track network can be accomplished during off peak periods without serious disruption to normal service. Use of crossovers and this control strategy also allows minimum disruption to service in the event of a train disablement. Trains of ten or more self-propelled vehicles are typically capable of operating at up to 80 miles per hour, and accelerating to 50 mph in less than 20 seconds. Service braking rates are approximately 3 mph-per-second with jerk held within ± 1.5 mph-per-second-per-second for passenger comfort. Trains run at the highest possible speeds between stations to provide average system speed including stops somewhat greater than 40 miles per hour with station spacings averaging one mile. Dwell times at each of the passenger stations generally vary between 10 seconds and 30 seconds depending on demand.

2.3 TRAIN CONTROL SYSTEM SAFETY REQUIREMENTS

Through most of its history, the rail rapid transit industry has had a reputation of being a safe mode of transportation. There have been relatively few catastrophies, with resulting fatalities, comparable to those experienced in other transportation modes.

Following is a listing of the types of accidents, roughly in order of their severity, which a rail rapid transit train control system is typically designed to preclude.

1. Train collisions.
2. Derailment and subsequent collision of a train with a major obstacle or other trains.
3. Doors inadvertently opening when train is moving at high or moderate speed.
4. Collision of a train with any major obstacle on the track including persons.

5. Inadvertent door closure on the limb of a passenger (while he is primarily outside the vehicle) combined with subsequent vehicle movement.
6. Derailment without subsequent collision with a fixed obstacle.
7. Inadvertent jerks from the propulsion or braking system resulting in minor injuries to passengers.
8. Inadvertent door closure on passengers causing minor injuries.

A variety of things can cause derailment, but derailment caused by improper switch alignment is the primary train control system related concern. Other safety problems such as fire, third rail hazard, and falls on station stairs, although important, are not usually associated with the requirements of the train control system.

To what extent have these types of accidents been precluded and what positive steps are being taken to prevent accidents, i.e., how does the industry address the safety issue? Safety is not usually defined quantitatively and is usually approached subjectively by instituting rules and procedures which, if followed, decrease the likelihood of accidents. "Moving People Safely, Safety Guidelines for Urban Rapid Transit Systems" is a recent publication that provides guidelines for such rules and procedures.[1]* The following excerpts are most directly applicable to this report.

> 6.54. Automatic Train Control (ATC)
>
> 6.5401. ATC must be operative for all prescribed train movements.
>
> 6.5402. The designated authority must be notified immediately of any ATC failure. His operating instructions will govern.
>
> . . . .

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*References are given in Appendix F.

Automatic Train Operation (ATO)

Note: These rules are in effect only when operating in ATO.

6.69. Use of ATO

6.6901. Train movements will be made in ATO over those portions of the main line, and other areas, and under those conditions prescribed by the Rules.

6.70. Operating Employee's Function

6.7001. Operating employee, when employed, must continually monitor performance of ATO.

6.7002. Operating employee, when employed, must take immediate action in the event of an ATO failure. Nature of failure and action taken must be reported as soon as practicable to the designated authority.

6.71. Communications Failure, Totally Automated Operation

6.7101. In totally automated operation employing no operating employee, a company representative must be stationed aboard a train when a known failure has occurred in two-way communications between any car in the train and the control point.

Although the safety goal, or safety standard, of a property is typically to completely preclude accidents, and safety guidelines like those mentioned above have been developed to help achieve such a goal, accidents do, in fact, happen. Unfortunately the actual safety performance (measured in accidents) of various overall rail rapid transit systems is not well documented in a form generally available outside individual properties. Data associated with just train control system-related accidents is even less available. It has been only recently that the Institute for Rapid Transit has developed a "Standard Form of Monthly Occurrence, Accident and Injury Reports" which summarizes the individual reports of eight major carriers in the United States. In general, these reports indicate that accident severity tends to be inversely proportional to the number of occurrences as would be expected. Deaths and major collisions are small in number compared to caught/struck by door accidents or to on-board falls caused by excessive vehicle jerk. The National Transportation Safety Board's

(NTSB) Special Study of Rail Rapid Transit Safety states that

> "Although railroad and transit accident statistics indicate that specific failures of signal systems do not cause a significant number of accidents, the limited scope of signal systems and train controls definitely causes accidents attributed to other sources. Man-failure is a significant accident source, and most accidents involving signals have been attributed to man-failure rather than to any aspect of signalling. The potential for accidents due to man-failure varies with the degree of control exerted by different signal systems in use in railroad and transit operations. Efforts to modernize and extend existing lines which perpetuate existing signal systems may fail to exploit opportunities to reduce so-called man-failure, even though the man is retained." (2)

Unfortunately, little has been done at a regulatory/government agency level to evaluate cause and effect of accidents and the relationships with the train control system design on an individual occurrence basis. Although various hardware standards and specifications exist, this Study uncovered no known successful previous effort to relate detailed accident statistics to quantitative technical requirements such as train control system equipment reliability. The current accident reporting system and the lack of a good historical data base made this Study difficult and tend to preclude the possibility of such efforts in the near future.

Recapitulating, the Study did not find a quantitative safety standard for an overall rail rapid transit system or for the control system aspect of the total system. There appears to be no definition of safety nor quantitatively how safe should a system be, and, by the same measure, how safe are existing systems. Little information was found on how different control system techniques affect safety. The closest thing to such a standard currently used, although not at all quantitative, is the fail-safe concept. Appendix C, titled "Automatic Train Control System Safety Criteria, Availability, and Reliability", discusses the fail-safe concept in detail and concludes that the fail-safe concept by itself is an inadequate control system design criterion for simultaneously ensuring high levels of safety and operational availability. Appendix C also proposes specific safety design criteria more appropriate for the total system safety problem and intended for application to new rail rapid transit systems development.

It is interesting to note that the National Transportation Safety Board issued a report during the course of this study titled "Safety Methodology in Rail Rapid Transit System Development" which recommends abandonment of the fail-safe concept and recommends an organized approach to accomplishing rail rapid transit system safety.[3]

2.4 WHY AUTOMATE THE TRAIN CONTROL FUNCTION

The concept of automatic train control typically combines all the functions required to operate trains without human intervention: regulation of individual train movement from starting to stopping; determination of routes, and control of scheduling to keep trains spaced for optimum train service. Three types of automatic control systems are typically employed. One, the train protection system, keeps safe separation of trains, prevents trains from exceeding the civil speed limits, and controls interlockings in a safe manner. The second, the train operation system, performs the on-board functions of velocity regulation, stopping, door operation, and starting. The third, the train supervision system, performs the centralized functions of train scheduling, operations, yard train control and maintenance management.

The level of automation of these train control functions has increased with time because of various purported safety, cost, and passenger service benefits. The train protection system, as the primary safety system, has been automated primarily because the human, when operating in a vigilance mode as a safety monitor, becomes unsatisfactory as motivational problems and failing alertness lead to unreliable performance. The train operation function, historically manual, has become more and more automated looking towards possible elimination of the train operator, (as a high cost item), increased ride comfort, and consistent performance (schedule). Attaining higher system capacity through shorter headways and shorter trip times also began, under the range of environmental and physical conditions, to tax the operator's reaction capabilities. To expedite passenger flow at each station, automatic program stop techniques have been introduced to provide precise stopping of trains at station platforms, (± 6 inches), under wide variations in conditions of approach velocity, grade, wheel-rail adhesion and passenger load. To increase passenger comfort and safety of standees, especially during starting and stopping, automation of these train operation functions was designed to limit jerk, the time derivative of acceleration, to acceptable levels. The train supervision function has become more automated primarily to expedite the smooth flow of trains, maintain schedules, coordinate maintenance, and minimize service disruptions.

The desire for features such as regenerative power from dynamic braking being fed back into the third rail and linked with precise management of relative train movements for system wide conservation of energy is a further reason, currently in vogue, supporting the case for higher levels of automation.

These purported safety, cost, and passenger service benefits are usually predicted for new systems or are used as part of the sales arguments for upgrading existing systems but, unfortunately, the actual benefits are generally not measured after implementation, compared with the predictions, and documented for general public availability. As a result, very little substantive, analytically supported justification for the trend toward increased levels of automation was found in the course of this Study. This does not mean that automation is not needed or justified, but it does hint that benefit predictions might be inflated. A disciplined analysis and an implemented documentation procedure related to this subject are needed to assist the important decision making processes being faced by designers of new systems.

3. AUTOMATIC TRAIN CONTROL (ATC) SYSTEM FUNCTIONAL REQUIREMENTS

The control system element of a typical rail rapid transit system, if implemented with a high degree of automation intended to achieve the operational requirements presented in Section 2.2, can be described by the functional requirements defined in the following subsections. Throughout this report, an Automatic Train Control (ATC) System is defined as <u>including</u> Automatic Train Protection (ATP), Automatic Train Operation (ATO), Automatic Train Supervision (ATS), and Communications subsystems as described below. Careful understanding of these terms as used here is required to avoid confusion since different properties and various elements of the rail rapid transit industry use these same or similar terms with a variety of meanings. A purposeful effort has been made to make the following set of requirements as purely functional, qualitative, and mechanization-independent as possible. This was done so that existing systems could be more objectively compared with these requirements as well as with each other in Section 4.

3.1 AUTOMATIC TRAIN PROTECTION (ATP)

The automatic train protection system helps to ensure train and passenger protection from collision, sideswipe, and derailment. The system does this by independently performing the following functions within its sub-systems.

3.1.1 <u>Train and Track Surveillance</u>

The train and track surveillance system detects the presence and critical behavior of all vehicles in the system and determines the status of the track network by

a. Determining the position of all switches and the general condition (weather, maintenance, etc.) of the entire track network as a function of time.

b. Determining the presence, identity, general condition, position, velocity, load, and intended route of all vehicles on the track network at all times.

3.1.2 Train Separation and Interlocking

The train separation and interlocking system provides route security along the track and through switches and maintains safe separation between trains by

a. Knowing safe braking distance of each train in the system as a function of train length, train load, position along the track, velocity, and track conditions.

b. Using the information from the train and track surveillance system.

c. Calculating and commanding safe switch locking and movement as a function of time for route security as train operations take place.

d. Calculating safe separation conditions and calculating and commanding corresponding safe velocity constraints for each train in the system as required to maintain safe separation.

e. Continuously monitoring the track network through the train and track surveillance system for switch locking and movement command conformance and initiating remedial emergency action in the event of non-conformance.

3.1.3 Train Overspeed Protection

The train overspeed protection system avoids the possibility of unsafe overspeed conditions by

a. Knowing the safe civil speed limit for all track as a function of position of a train along the track, direction of train travel, and intended route through switches.

b. Using the information from the train and track surveillance system.

c. Knowing the safe velocity constraints for each train in the system required for safe separation as determined by the train separation and interlocking system.

d. Calculating and commanding safe maximum velocities, based on civil limits separation considerations or special conditions of the track network, at which each vehicle in the system can move from its current state.

e. Continuously monitoring all vehicles through the train and track surveillance system for maximum velocity command conformance and initiating remedial emergency action in the event of non-conformance.

The automatic train protection system through its train overspeed protection subsystem imposes an upper bound at all times on velocity of each vehicle in the system in order to maintain system safety. In addition, vehicles may receive lesser and overriding velocity commands from the automatic train operation or automatic train supervision systems for purposes of maintaining passenger comfort or a particular time schedule.

3.2 AUTOMATIC TRAIN OPERATION (ATO)

The automatic train operation system performs the on-board functions of train velocity regulation, programmed stopping, door operation and starting for the safety and comfort of the train and passengers. The automatic train operation system on each vehicle does this by performing the following functions.

3.2.1 Train Velocity Regulation

The train velocity regulation system maintains the velocity command requested by the automatic train supervision system and approved by the automatic train protection system except as modified by the programmed stopping subsystem and the door control and starting subsystem. The train velocity regulation system does this by

a. Determining and acknowledging the velocity command as a function of time as requested by the automatic train supervision system, and as approved by the automatic train protection system, or as interrupted by either the programmed stopping or door control and starting subsystems.

b. Determining the current velocity and passenger load of the vehicle together with track condition, such as grade and coefficient of friction.

c. Commanding the appropriate magnitude and sign of acceleration that is within the acceleration and jerk constraints required for passenger safety and comfort and also necessary to maintain the actual vehicle velocity in conformance with the commanded velocity.

3.2.2 Programmed Stopping

The programmed stopping system generates the velocity command interrupt to the train velocity regulation system as required to accomplish stopping at stations by

a. Determining the necessary relative position information between the train and approaching station.

b. Determining the velocity profile consistent with a planned stopping point at the station.

c. Commanding the train velocity regulation system in accord with the determined velocity profile.

d. Inhibiting the programmed stopping function for station run-through in response to a command requested by the automatic train supervision system and approved by the automatic train protection system.

3.2.3 Door Control and Starting

The door control and starting system maintains passenger safety with regard to train doors by

a. Precluding door opening while the train is moving.

b. Precluding door opening unless the train is indeed stopped, with locked brakes, and properly positioned at a station such that all passenger doors on at least one side of the vehicle are adjacent to a station platform.

c. Inhibiting brake release and traction power prior to door opening.

d. Commanding door opening for a minimum station dwell time predetermined by the automatic train supervision system for doors on that side of the train adjacent to a station platform.

e. Inhibiting door closure after the minimum dwell time has elapsed and until all passengers and their possessions are determined to be clear enough to allow door closure.

f. Commanding door closure.

g. Verifying door closure or opening and closing the doors as necessary to ensure that all the doors are in fact closed and locked and that all passengers and their possessions are, in fact, inside the vehicle.

h. Inhibiting door opening after verifying door closure and removing inhibition of brake release and traction power, allowing the train to start by reverting to control by the train velocity regulation system.

3.3 AUTOMATIC TRAIN SUPERVISION (ATS)

The automatic train supervision system performs the centralized functions of train scheduling and operational implementation, yard train control, automatic train control system maintenance management, and overall system maintenance management. The automatic train supervision system does this by performing the following functions.

3.3.1 Train Schedule Design and Operational Implementation

The train schedule design and operational implementation subsystem designs nominal daily and holiday train schedules, continuously updated based on the real time situation of failures, emergencies, and abnormalities, as they evolve throughout the system on a given day. The subsystem commands train operations to best accomplish the schedule safely by

a. Determining the safe nominal identity, position, velocity, and intended route of all vehicles, as a function of time, throughout a given day, based on demand analysis, simulation, and past experience.

b. Determining the corresponding nominal velocity command schedule for each train and the corresponding switch position command schedule for each switch as a function of time for a given day that is commensurate with the automatic train protection system safety constraints.

c. Determining, from the train and track surveillance system, the actual identity, position, velocity, intended route, and general status of each train, and the actual position of each switch as it is changed, throughout the day.

d. Collecting, processing, and acting on all data related to equipment failures, abnormal situations, and emergencies throughout the transit system.

e. Initiating nominal or updated train velocity and switch position commands which best maintain the nominal or updated schedule but which are subordinate to automatic train protection system safety constraints. Such actions include temporary storage of disabled trains and removal of trains from revenue service for storage or maintenance. The automatic train supervision system requests routes, movements, and various actions which the automatic train protection system must approve as safe. Otherwise, alternative routes or schedule revisions must be generated.

f. Maintaining a data file on past system performance to aid in the development of realistic, demand responsive schedules and proven train system management strategies to be used to minimize the impact of known types of system failures, to provide minimum safe headways where required, and to minimize system delays.

3.3.2 Yard Train Control

The yard train control subsystem exercises control over trains operating throughout the various yard facilities and over trains departing to and returning from revenue service by

a. Providing transfer track zones wherever trains transfer between revenue operation on the main line and storage or maintenance status in the yard.

b. Managing the process by which single vehicles are hostlered into trains, moved into the transfer track zones, and dispatched for revenue service.

c. Managing the process by which trains are removed from revenue service through the transfer track and routed into and through the yard for maintenance or storage.

Note that many of the functions already described in Sections 3.1, 3.2, and 3.3 are equally applicable to yard train control, but are generally mechanized differently (lesser degree of automation) because of less demanding operational requirements (speed, headway, schedule, etc.) than of revenue service. It is most important that a safe method of transition be provided between the two different sets of procedures/mechanizations.

3.3.3 Automatic Train Control System Maintenance

The automatic train control system maintenance subsystem is a support function within the total automatic train control system. It uses all the resources of the system to prevent, detect, cope with, and repair system malfunctions thus minimizing revenue service delay and passenger inconvenience by

a. Utilizing preventive maintenance techniques.

b. Utilizing self check features and automatic maintenance techniques such as electronic testing, data processing, and maintenance record storage.

c. Utilizing inherent and planned system level redundancy and on-line malfunction detection to allow degraded but safe operational performance until repair can be accomplished.

d. Utilizing the communication system (Section 3.4) effectively to manage automatic train control system maintenance resources and keep current on maintenance status as it affects system operation.

3.3.4 Overall System Maintenance

The overall system maintenance subsystem is a support function within the total automatic train control system. It uses system and other resources to prevent, detect, cope with, and repair all transit system malfunctions other than those associated with the automatic train control system so as to minimize revenue service delay and passenger inconvenience. Continuous and timely track network, station, and especially vehicle maintenance status is crucial to overall train system supervision. Since the train and track surveillance, automatic train operation, and communications elements of the overall automatic train control system are the mechanisms by which malfunction detection and preliminary diagnosis are basically accomplished, it is logical to manage the rest of the actual maintenance process as part of the automatic train supervision system.

3.4 COMMUNICATION SYSTEM (CS)

The communication system performs the widely distributed functions of data and voice communications to unify and support all other elements of the automatic train control system. The communication system accomplishes this by conveying commands, data and other messages between the components and subsystems physically separated throughout the system.

3.4.1 Normal System Operation Communications

Automatic train control subsystem equipment is typically physically distributed on the vehicles, along the wayside, in stations, in local area "towers," and at a central control facility. A flow of commands, data or other messages between these various physical locations tie various components, subsystems and personnel together to perform the following normal automatic train control system functions:

Train and track surveillance

Train separation and interlocking

Train overspeed protection

Train velocity regulation

Programmed stopping

Door control and starting

Train schedule design and operational implementation

Yard train control

Automatic train control system maintenance

Overall system maintenance

Communication links to perform these different functions may be common, separate, or mixed. Communication between vehicles or roving personnel (maintenance or security) and the wayside is typically accomplished by radiative or inductively coupled devices because of vehicle and personnel motion. All other communication links between fixed location component or subsystem elements may be cable. Command verification assurance techniques and message error rates must be suitably designed in proportion to the consequences of error for each communication link and in proportion to the interference anticipated from propulsion or power generating apparatus. Data rates for some automatic train operation and automatic train protection function communication links are generally among the highest in the system since those links may be part of closed loop servo systems.

3.4.2 Emergency Communications

In case of failure of a normal system operation communication link, a redundant communication mode should always be available to effect continuous operation and maintain surveillance for safety. The communication form may be voice if an on-board operator is incorporated in the system, or other forms if remotely programmable equipment is on board the vehicle. The link might take the form of a radio telephone or it might be an inductively coupled communication line.

4. COMPARISON AND PROBLEMS OF EXISTING TRAIN CONTROL SYSTEMS

This Section discusses some of the problems and safety aspects of existing automatic rail rapid transit train control systems.

4.1 COMPARISON OF EXISTING TRAIN CONTROL SYSTEMS

Appendix A tabulates system characteristics of some rail rapid transit properties relative to the subsystem functions and terminology developed in Section 3. It also contains a comparison of additional characteristics, primarily in the areas of vehicles, track and stations, and system operational considerations.

Some of the points developed from Appendix A are

a. Automatic, basic train protection functions are almost universally accepted. However, the train and track surveillance function of the train protection system is performed in a variety of ways. The particular entries in Appendix A are for the most automated lines of the larger and older properties. Each of these properties, has, in general, its own internal variations depending on equipment vintage of different lines.

b. A wide variety of automatic train control system component technology exists, but there is no universally accepted, off-the-shelf, surveillance system design meeting the requirements for all new rail rapid transit systems. The wide variety of design alternatives such as continuous detection or not, welded rail or not, and rubber tire or not, together with wide variations in wayside environment (electrical, mechanical, and weather) currently preclude a universal answer with present systems.

c. The majority of systems use block occupancy as the basic surveillance information quantity instead of higher forms of information such as on-board derived velocity, or more precise position determination within a block.

d. It is technologically feasible to design a completely automatic train control system such as the BART system. However, there are no properties having sufficiently protected, exclusive rights-of-way to permit considering the complete elimination of the human, on-board operator for surveillance.

e. The basic train operation functions of train velocity regulation and stopping are implemented with various degrees of automation and human operator participation according to property-specific motives/designs.

f. The door surveillence function in different systems is performed over a wide range of automation levels ranging from BART's optional inhibition of otherwise fully automatic doors by the train attendant, to the MBTA's employing one conductor for each two-car pair.

g. The train supervision function is generally most automated in the newest rail rapid transit systems since system-wide upgrading of the central control facilities of older properties is more difficult than gradual improvements in train protection and train operation, or the provision of new vehicles on a single section of the system.

h. All systems have, or plan to have, voice communication between each train operator and the train supervision (central control) function.

i. There are a wide variety of train supervision system techniques, especially with regard to how functions are implemented and physically distributed among a central location, "towers," station control, and the wayside. Of particular importance is the degree to which computers are employed for repetitive, housekeeping, or decision making functions.

j. There has been an historical trend toward increased levels of automation but there is little substantive evidence to justify this trend based on information gathered during the Study.

k. There are essentially no specific safety criteria except the goal to preclude all accidents. Even if such criteria existed, there are insufficient accident statistics for evaluating absolute safety of a particular line or to measure a line's relative safety either compared to other lines of the same property or lines of other properties.

l. It follows from (k) above that there is no known quantitative or satisfactory qualitative way of relating the degree of safety of any rail rapid transit system to the particular degree of automation used in its train control system.

m. The process by which each rail rapid transit system is declared safe for use by the public varies from property to property. Some properties have a local, responsible agency; others self certify their own system.

4.2 PROBLEMS WITH EXISTING TRAIN CONTROL SYSTEMS

Although many of the properties listed in Appendix A have been operating their train control systems for many years, problems do exist which are the subject for constant development programs. A partial list of such problems follows.

4.2.1 Train and Track Surveillance Problems

Appendix B treats communications for rail rapid transit systems and describes some train surveillance systems as well as some of the problems encountered in designing such systems to be highly reliable and fail-safe. The surveillance system is the heart of the train control system since attainable levels of train safety and control are set by preciseness of knowledge on train location and what a train is doing relative to other trains. A stringent design requirement is for continuous fail-safe detection of a train in a block under a variety of changing electrical, mechanical, and weather conditions. In practice, this requires a fair complexity of electrical equipment for each block. Types of brakes, the wheel rail interface, car weight, the moisture environment, and rail joints are among the factors having important impact on the design, testing, and reworking of new train surveillance systems.

Providing additional control information beyond simple block occupancy, such as train identification, time of transition between blocks, train velocity, or precise position of the train within the block, adds complexity to the surveillance function. The difficulties of obtaining more control information to accomodate higher speeds at lower headways must be traded off against the benefits of having simple devices with low part counts, high reliability, infrequent failure, and requiring little maintenance.

Current surveillance systems generally employ the running rails as conductors and the wheel-axle-wheel units as shunts in the train detection track circuit. The rails are also usually used as the ground return for third rail power and carry all sorts of electrical noise. Furthermore, other electrical properties of the wheel-rail, rail-tie, and tie-ballast interfaces under various moisture and aging conditions vary considerably and further complicate the surveillance system design process as discussed more thoroughly in Appendix B.

Another approach, using other conductors along or between the rails in place of the rails themselves, is much more costly for the initial installation. However, such systems may be less costly to maintain in the long run. This approach is generally necessary if precise position information within the block boundaries is required.

Both approaches generally involve electrical equipment located between the rails. This equipment is therefore in the electrical noise environment generated by the passing propulsion systems.

It should be emphasized that no thorough analysis was found during this Study which parametrically and dynamically related critical control system characteristics, alternative surveillence quantities, system nonlinearities, and human operator skills. Lacking such information it is not possible to make definite design decisions regarding optimum automation levels and surveillence system complexity to satisfy any particular set of operational requirements. Although the basic thrust of this Report is towards higher vehicle speeds, lower headways, and increased control system automation, it is recognized that the realistic, undemanding operational requirements for some new systems could be properly met without any of these three ingredients.

4.2.2 Train Separation and Interlocking

Train and track surveillance information for each block and switch position, train braking characteristics, and civil engineering information on such factors as grades and turns, are major ingredients for the design of a system to perform the train separation and interlocking function. Such a system must generate allowable maximum safe speed profiles for all trains in the system.

More route flexibility means more switches. Provision for additional storage of disabled trains means more switches. More switches mean more blocks requiring interlock protection and more logical combinations and permutations of possible relative train positions or desired routes. Desire for shorter and shorter headways to increase overall system capacity generally means more and shorter length blocks or higher forms of surveillance information than just block occupancy. Such changes in operational requirements generally disproportionately increase the complexity of the train separation and interlocking function.

Ensuring integrity of the logic design is necessary to safety. Also contributing to the overall safety level are proper maintenance of the drawings to define all possibilities, correct hardware implementation of the logic design in the field, allowance for non-ideal considerations such as circuit design latitude for temperature variations, and a detailed fault analysis. These are all difficult, time consuming problems and should all be examined thoroughly as part of a safety certification process during initial installation, test, and rework prior to revenue passenger service. They must also be periodically examined and considered in later time to ensure continuing high safety levels.

4.2.3 Train Overspeed Protection and Train Velocity Regulation

There has been a long history of automatic overspeed protection devices particularly for protection of trains on dangerous trackage around curves, across bridges, and through crossovers. Classical signaling system techniques including associated "train stop" and "trip cock" devices are still common on many lines throughout the world.

Current technology in automatic train operation systems improves safety by providing constant comparison between commanded speed and actual speed. In a fully automatic system, the error signal between these two quantities goes to the propulsion and braking system for velocity regulation. If the actual velocity exceeds the commanded velocity and the normal braking system has not been actuated within a few seconds, additional logic actuates emergency braking to stop the train. If a train operator is required to accelerate, decelerate, and regulate velocity of the train in response to velocity commands from an otherwise automatic train operation system, some form of annunciator typically sounds if overspeed occurs, and the operator must activate braking within a few seconds or the emergency braking system will take over.

The major problem with these systems is that not only must they be fail-safe and highly reliable but they can fail only infrequently; otherwise passenger service becomes intolerably disrupted. This matter is treated more fully in Appendix C. Failure may occur in the generation of the speed command, in the comparison between actual and commanded speed, or in the interpretation of the commanded error signal by the propulsion system. Typically this involves on-board equipment, wayside equipment, or equipment housed in stations. As a result, the diagnostic and maintenance problems are widely distributed and their solutions are potentially time consuming.

4.2.4 Programmed Stopping

Station platform lengths are usually set by the length of the longest train intended to be run in the system, since subway station construction costs are high. Therefore, stopping location tolerances may be low. Automatic programmed stopping techniques have been demonstrated which can stop a train ± 6 inches from an intended point under ideal conditions. These techniques have opened up the possibility of having doors or train screens on the platform for increased safety. Such stop-location accuracy, under all possible conditions of train load, approach trackage shape, and weather conditions is difficult to maintain. If the automatic system is designed for a conservative worst case condition using low deceleration rates, then a minimum trip time is not achieved when more typical, better conditions exist.

Station undershoot is a relatively easy error to correct but station overshoot is not. Backing up is dangerous and many systems, therefore, have a "no backup" rule or at least require the operator to move to the rear of the train to reverse train direction. This practice usually causes a significant delay. The alternative of simply progressing to the next station without opening the doors is a serious inconvenience, at least to some of the passengers. Door control during overshoot or undershoot is critical if safety hazards are to be avoided.

Backup after extensive overshoot may seriously compromise system safety by confusing the logic of the train separation and interlocking system which is programmed assuming unidirectional motion except in certain track sections.

4.2.5 Door Control and Starting

This particular problem is a long standing nuisance to the rail rapid transit industry. It is handled in a variety of ways, primarily using visual surveillance and human judgment. It is discussed in greater detail in Section 5.6.

5. FUNCTIONAL ROLE OF THE HUMAN OPERATOR

All of the functions defined in Section 3 were intentionally set forth with no a priori commitment to any particular system mechanization procedure. The purpose of this Section is to highlight those functions which historically have proven difficult to automate and/or have not successfully been automated and which have a significant impact on safety. The emphasis is on safety-related train control functions rather than other concerns such as operational strategies, train security, passenger information, and maintenance diagnosis, which the human operator has historically handled, but which are less directly related to safety and to the automatic train control system design.

The functions described in Section 3 which have the highest sensitivity to safety and which the human operator has been known to accomplish effectively in the past are listed below.

Train and track surveillance

Train overspeed protection

Train separation and interlocking

Train velocity regulation

Door operations

This is not meant to imply that the other functions listed in Section 3 have no link with safety, or that the human operator has been known not to accomplish the others effectively in the past. The listing of functions above is somewhat parallel to the listing of the types and severity of accidents which an automatic train control system is typically designed to preclude, as described earlier in Section 2.3.

5.1 CRITICAL BEHAVIORS REQUIRED OF THE OPERATOR

The activities that the rail rapid transit train operator, or train attendant (referred to here as the operator) performs can be described in terms of five basic behavior categories: sensing, vigilance, pattern recognition, controlling, and decision making.

a. Sensing - The physiological process of detecting and processing stimuli representing changes in the operator's environment.

b. Vigilance - The monitoring of a parameter or set of parameters in order to detect some change which requires a response.

c. Pattern Recognition - The organization and categorization of complex event patterns which may contain a large proportion of non-standard elements.

d. Controlling - The maintenance of some parameter or set of parameters within preset or required boundaries through manipulation of a control or controls.

e. Decision Making - The choosing between options or categories based on training and outcome expectations.

5.2 TRAIN AND TRACK SURVEILLANCE

In automatic systems which include an on-board operator, a primary duty of the operator is to visually survey the right-of-way for features or events which could be dangerous to his train, following trains, or trains on other tracks. The operator is also required to survey visible portions of opposing trains and to monitor the condition of his own train.

5.2.1 Right-of-Way Surveillance

It is expected that each automatic rail rapid transit system will have an exclusive right-of-way with proper safeguards such as fencing, guardrails, and other required protection. However, experience reveals that even those rights-of-way intended to be exclusive will be violated. In a well regulated system such violations should be rare, but in high speed systems any violation might be catastrophic.

Right-of-way violations can range from small animals and vegetation on the track up to vandal-erected barricades capable of derailing a train. If an operator is included to augment the automatic system he can detect such violations and take safeguarding action and/or summon emergency aid. He can also survey the right-of-way for structural damage and potential danger situations, again taking possible safeguarding action and informing the train supervision system for appropriate further action.

Visual right-of-way surveillance taps two behavior categories: vigilance and pattern recognition. An operator must be vigilant, alert, and attentive to the safety-critical elements of the right-of-way. His performance in carrying out the surveillance task is a function of his physical condition, task loading and motivation.

Operators can and should be selected on the basis of good health and be screened for obvious symptoms of illness before going on duty. Precautions can and must be taken against alcohol and drug involvement while on duty. In a well regulated system, good physical condition of the operator is mandatory.

Excessive task loading is not normally a problem since action resulting from right-of-way surveillance is generally characterized by a low event rate. Motivation, however is usually a problem. In general, to maintain operator motivation, it is necessary to keep the task loading above the boredom level and to make the tasks meaningful. "Make-work" tasks, or those perceived by the operator as such, are not satisfactory. It is also important that the operator feel that he is an integral part of the system. His work station and duties should not appear to be vestigal additions. It should be noted that vigilance is not the human operator's strong suit and, in general, automatic systems are superior in this regard.

Of all man's abilities the one which is most difficult to equal or surpass by machine is pattern recognition. The human operator is equipped with highly sophisticated sensory mechanisms and the ability to integrate non-standard sensory inputs and place them in categories to be used as the basis for decision making. It is doubtful that in the near future an automated vehicle will be able to equal a human operator in recognition and decision capabilities.

5.2.2 Surveillance of Other Trains

The operator can survey the exterior of other trains to detect potential hazards. While such surveillance is always desirable, it may not always be possible due to the rapid closing speeds and small clearances between trains.

5.2.3 Surveillance of the Condition of the Operator's Train

In an automatic system which includes an on-board operator, the operator must continuously monitor information provided by the train's displays and verify it against established safe ranges and directly sensed, exterior events. To a large extent, verifying display information against safe ranges is simply a vigilance task. As such, for reasons presented above, such verifications might be better accomplished using redundant check circuits with redundant on-board or trackside sensors. The second task, that of comparing display readings with exterior events, can be performed by an operator or by equipping the train with the circuitry necessary for complex consistency checks of sensor functions.

The operator, through sensory perception, can also detect unusual vibration, sound, smoke, odor, light and other indications of potential failures. Such operator sensory capabilities are more sensitive, flexible, and sophisticated than those of automated systems.

5.3 TRAIN SEPARATION AND INTERLOCKING

With the exception of small switch yards this function has not, historically, been an on-board operator task, nor should it be. Primary safety for all train systems is a function of the automatic train protection system which determines safe separation and interlocking strategies and relays these to the train. The automatic train supervision system provides maximum velocity commands to the train and position commands to the switches. In the event that an operator is included and he is expected to continue train operation after failure of the automatic train protection system, he should be provided with in-cab or trackside displays representing desired velocity, switch position, and block occupancy. When provided with such information the operator can be expected to maintain a reasonable level of service with an inoperative automatic train protection system.

5.4 TRAIN OVERSPEED PROTECTION

Train speed is maintained through provision of velocity command signals by the automatic train protection system. In the event of failure of this system, the on-board operator can detect overspeed by comparing the actual speed, as displayed on his speedometer, with the commanded speed and take remedial action.

5.5 AUTOMATIC TRAIN OPERATION

The automatic train operation function is the one usually intended to supplant the human operator or make him redundant. A fully automatic train operation system provides automatic velocity regulation, automatic acceleration and deceleration profiles, and automatic train position for programmed stopping.

5.5.1 Automatic Velocity Regulation

In fully automated systems, the train accelerates and decelerates according to preprogrammed profiles designed to reach the velocities called for by the automatic train supervision system. The operator, if provided with in-cab signals and/or commanded velocity signals, can operate the train in a normal manner when there are on-board failures in the automatic train operation system. If such signals are provided, along with the block occupancy and switch position indicators required for safe operation, the train operator can take command when such non-standard conditions as slippery track, high wind loadings, passenger overloading, or heavy snow render the preprogrammed acceleration-deceleration profiles invalid. Safety in this "semi-automatic" mode depends on trained operators. Opportunities, therefore, must be given for practicing this mode of train operation. This practice may be gained in part through simulation of normal and emergency conditions but it should also include operation at regular intervals under real revenue service conditions.

5.5.2 Programmed Stopping

While properly an element of velocity control, programmed stopping also involves location of the train at the station, determination of significant overshoot or undershoot, and correction if either is present and the correction can be safety made. An on-board operator can, of course, perform these functions. Corrections for overshoot or undershoot tap two behavioral categories: controlling and decision making.

5.6 DOOR OPERATIONS

The automatic door operations system is intended to cause the train doors to open properly when the train is stopped and correctly positioned at the station, to preclude train movement while the doors are open, to begin door closing after a predetermined time and to complete closing after the passengers have cleared the doors. Though a part of the automatic system, the doors must be manually operable in emergencies.

Automatic door operation probably provides the greatest challenge to full automation. The door sensors must be able to distinguish between human appendages and small objects which are caught accidently or placed purposely between the doors. In peak passenger flow conditions a judgement must be made to stop the flow based on waiting time, car capacity, and expectation of further passengers.

"Fooling with doors" is a favorite type of horseplay among children, even on trains with conductors whose major function is door control. It should be noted that school age children constitute a significant segment of the ridership on most rail rapid transit systems.

Finally, in emergencies such as fires, floods, structural collapse, or derailments, prompt opening of train doors in only those areas safe for passenger egress, is critical. This type of emergency situation requires convenient overriding of the automatic system. However, the overriding function cannot be so convenient as to allow vandalism and inappropriate door opening.

The door opening functions, if assumed by an on-board operator, require both pattern recognition and decision making based on non-standard elements. Most of these functions are better managed by a human operator and some, such as avoiding horseplay during door opening, can only be accomplished by a human operator.

5.7 ON-BOARD EMERGENCIES

Although not strictly a control function, the on-board operator can sense emergency conditions such as fire, excessive vehicle vibration, or other anomalies, particularly while the vehicle is in motion, and can initiate an emergency stop.

5.8 ON-BOARD MAINTENANCE

The on-board operator can and is often required to make simple repairs and adjustments to the train equipment. The presence of an operator provided with training, simple tools, and a communications link to knowledgeable service personnel can overcome many minor problems that might otherwise cause system delay.

The need for a field-repair-trained operator is most likely to be critical in the initial phases of system operation when on-board diagnosis can aid in shortening system shakedown and reduce the consequences of shakedown-related failures.

5.9 DETERMINING THE NECESSITY FOR THE USE OF AUTOMATIC TRAIN OPERATION

In the design of advanced rail rapid transit systems, any number of reasons are given for supplanting the train operator with an automatic train operation system.

a. The transit system requires very rapid decision making because of short headways and high speeds.

b. The transit system requires rapid and accurate velocity modifications to accommodate the complex and nonrepetitive routing instructions provided by the automatic train supervision system.

c. The system requires very precise control of velocity, acceleration, deceleration, and station dwell time in order to accomodate varying traffic flow and minimize on-board accidents due to excessive jerk.

The assumption made in justifying automatic train operation is that the on-board operator is too slow, unpredictable, expensive, or otherwise unreliable to perform adequately. In order to decide on the need for a potentially more expensive and possibly troublesome automatic train operation system these assumptions should be tested during the early design phase of each system.

This testing requires access to two kinds of information. The first, system specific parameters, includes factors such as minimum design headway, maximum design speed, maximum merge rate, minimum acceptable control precision, and maximum design decision rate. This type of information should be available early in the system design phase. The second, human operator performance parameters, concern the capability of the operator to perform critical tasks in the system under consideration. It includes measures of operator performance precision and rate, and statistically determined expected ranges for such performances. To some extent it is possible to extrapolate estimates of these performances from previous research on basic operator capabilities. However, it is likely that more directly applicable data can be acquired through the performance of laboratory experiments using train cab simulation, validating simulation-acquired data through actual observation of operators during revenue operation.

It is good engineering practice to carefully verify the design rationale used in selecting the level of automation for any new automatic train operation system. Verification should be accomplished by extensive test, evaluation, and rework prior to opening revenue service.

6. CONTROL SYSTEM DESIGN: REQUIREMENTS, METHODOLOGY, AND VERIFICATION

This chapter discusses the design of a rail rapid transit control system. In particular, it covers those factors that the overall design process must include; a determination of requirements, a procedural means of realizing these requirements and, finally, a verification process to ensure that the system meets the requirements. These three major elements of the control system can be provided using the established techniques of systems analysis, control system design, computer simulation, laboratory tests and field demonstrations.

Requirements, design methodology and verification each have a hierarchical structure; operational, functional, design, and implementation requirements.(1) Commensurate with each of these groupings, there must be pertinent evaluation criteria that provide a means for computing figures of merit for each particular implementation alternative. A quantitative measure of system safety is an example of such a figure of merit. A control system design methodology, an important requirement for rail rapid transit control systems, must link the entities of requirements and verification together. The control system design methodologies that have been successfully developed and applied to aerospace, military, transportation, and particularly industrial process control problems represent a large reservoir of experience and information applicable to the development of such methodology for the design of new rail rapid transit train control systems.

6.1 CONTROL SYSTEM DESIGN REQUIREMENTS

The primary operational requirement of any present day rail rapid transit train control system is to provide safe operation under all conditions. Specifically, the historical development of train control techniques has led to the fail-safe principle that any malfunction affecting safety will cause the system to revert to a state that is known to be safe. Operationally, the typical required safe condition is that train operations be halted, (shut down), until the failure has been determined and the situation resolved. This operational principle is usually not compatible with the requirements to operate at maximum capacity and adhere to a nominal schedule. Both of these requirements are of critical importance for an efficient and reliable mass transit system.

Since it is imperative that none of these requirements be unnecessarily compromised due to a system, subsystem or component failure, the train control system must have the capability to:

a. Continually assess system status to ascertain the state of those subsystems that are pertinent to any control function and to identify a failure.

b. Assess the effect of a failure(s) upon the pertinent control functions.

c. Select that modification to the control system that minimally compromises system capacity and schedule, and, of prime importance, that maintains the fail-safe principle.

d. Monitor and ascertain failure resolution.

e. Resume or continue nominal operation.

The foregoing requirements give direct rise to the functional configuration of Figure 6-1. This representation, although general, does provide direct insight into the required configuration of a rail rapid transit control system. It shows that the control system is a closed-loop, feedback control system that must maintain its integrity at all times and, in case of failure, allow minimal compromise of system performance with no compromise of safety. The system can be defined functionally as the aggregate of separate functions identified in Section 3. The functional system of Figure 6-1 should, therefore, have a closed-loop operation for each of those separate functions. A more detailed presentation of this concept is offered in Section 7 and elsewhere.(2,3)

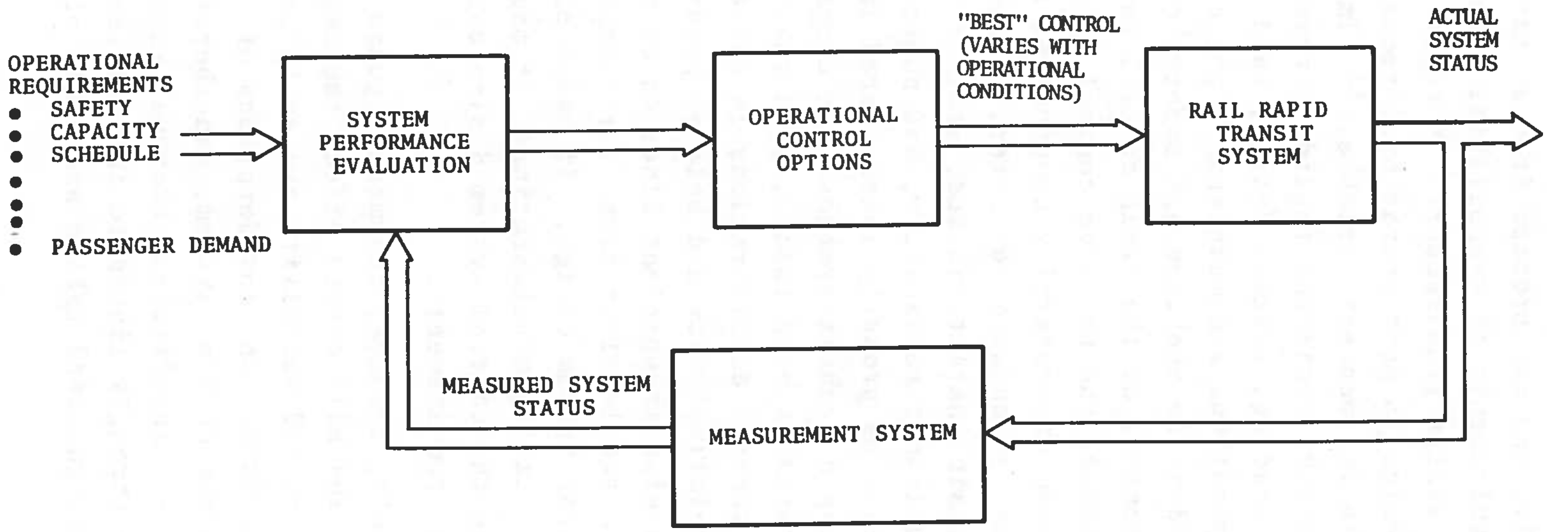


Figure 6-1 Closed Loop Representation of a Rail Rapid Transit System

Typically, one can proceed from a statement of operational and functional requirements to capabilities a to c above, and then, to more detailed design requirements. However, the ability of any control system design to meet operational requirements and specifications is not an independent variable.(4) Improper, early top level planning and design decisions regarding track layout, route structure, station spacing, station design, land acquisition, personnel complement, operations and maintenance philosophy and similar matters can seriously degrade the inherent safety, operational capability, and growth potential of the train control function. With so many variables involved, the required control system capability can be inadvertently and unnecessarily compromised at the time of procurement, laying the groundwork for later, serious problems. Demand predictions, train characteristics, weather condition extremes, scheduling, equipment reliability, and numerous other important factors must also be properly interrelated in the process of designing rail rapid transit systems. In competition with such political concerns as bond issues, land taking, and ecological impact, train control considerations in system design have tended to receive a relatively low and belated priority. The decision to merge two otherwise independent lines on common trackage instead of incorporating a two level station, for example, has far reaching impact on control system design. If based only on station structure design and land taking considerations, it might be made incorrectly and could leave the control system design overspecified in light of the operational requirements.

How tunnels, bridges, abutments, guard rails, fences, stations, blind corners, and hill crests affect the degree of independent right-of-way protection and visibility are early structure decisions that have tremendous impact on considerations of safety and the proper role of man in the control system, and therefore, on long term operations costs. Insufficient storage tracks, crossovers, and yard facilities are strongly linked to insufficient early attention to track layout design, land taking and route planning. These elements contain the potential for serious operational delays, hazardous single track operations, and even serious temptations to compromise safety in non-normal event control system situations.

Track layout designs should contain the minimum possible number of headway bottlenecks, especially at terminal turnaround points, merge points, and shared trackage in close-spaced downtown subway stations. New designs should include provision for growth at these choke points in the form of sufficient space for parallel trackage, additional station platforms, vehicle storage tracks, additional turnout positions and larger tunnel structures. At a minimum, necessary land rights should be acquired. Train control system expertise applied at an early stage must be integral to the initial transit system planning and design process in order to minimize the number of irrevocable constraints upon control system design and operation.

6.2 CONTROL SYSTEM DESIGN METHODOLOGY

There are several additional requirements, evident from the foregoing operational and functional requirements, for the development of a control system design methodology. They are

a. Identify and define those critical train control functions related to maximum capacity, scheduling, passenger safety and the fail-safe principle.

b. Identify the input and output information requirements for each control function. In general, the location of the responsibility for the control function (i.e., central, tower, station, wayside, vehicle) or implementation (hardware, software, human operator) will be independent of the information requirement. However, for a given location of control function responsibilities, there exist alternative communication paths as shown in Figure 6-2. For safe operation of each control function, a two way communication path must always exist between the control function, its source of responsibility, and the source of the supervisory function.

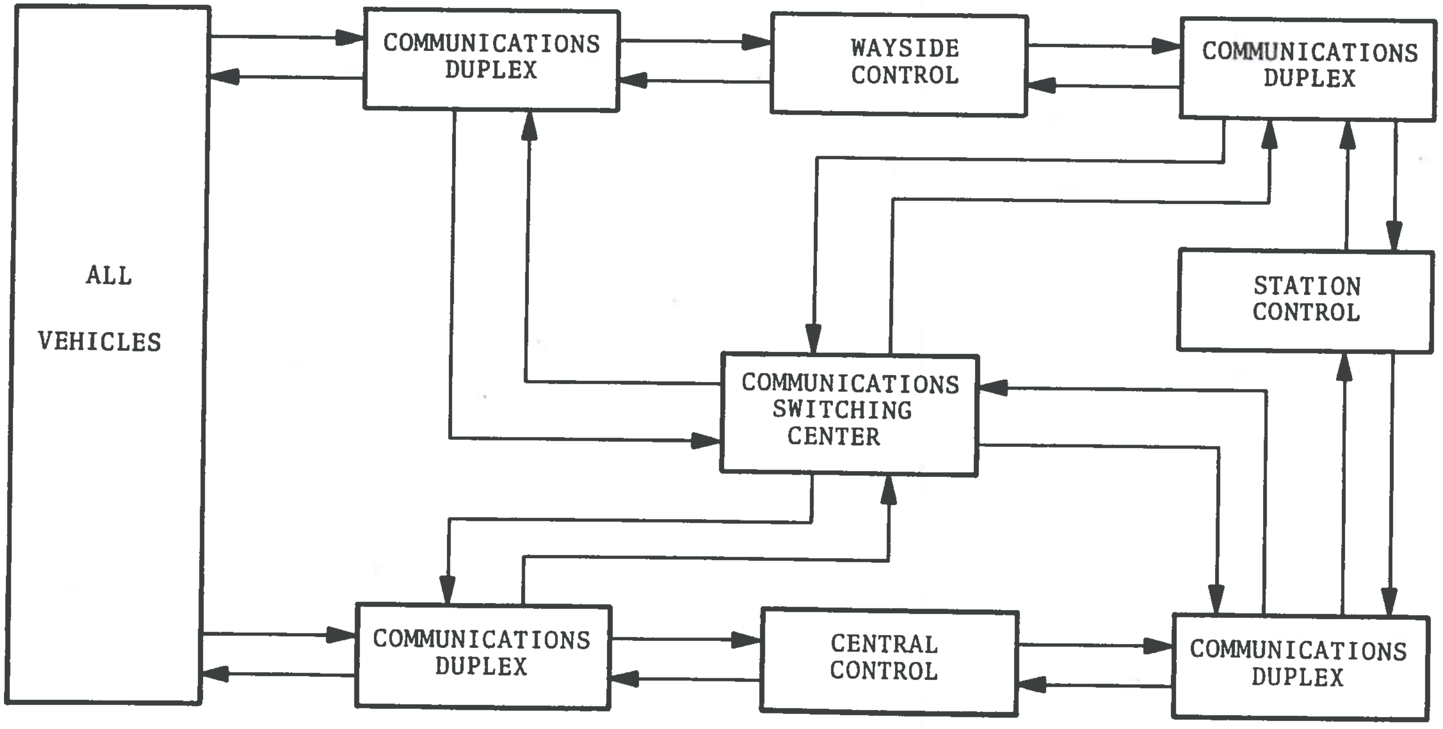


Figure 6-2 Alternative Communication Paths

c. Identify the data processing requirements for each control function and its pertinent input/output information requirements.

d. Determine the dependence of the information and processing requirement upon the control system configuration, i.e. the location of the responsibility for the various control functions both in the primary and back-up modes.

e. Identify potential failures within the surveillance system, communication system, and control mechanisms. Assess the effect of each potential failure (single and multiple) upon the integrity of each control function and, when so compromised, the integrity of the supervisory function in maintaining overall system safety. Also identify the effect of each potential failure on achieving specific measures of system requirements.

f. Given the "sensitivities" of (e) above, determine the information and control system requirements for safe, efficient transient operation, that is, transition from primary to back-up control policies and from back-up to primary control policies.

g. The sensitivities of (e) and (f) above then provide the necessary and sufficient data base for configuration design of the control system.

There exists an abundance of application oriented documentation that is addressed to control system design techniques, practices and methodologies for large, complex systems. In particular, the functional and quantitative relationships between the various subsystems and the quality of control, as measured by accepted standards of system performance, are well known. As an example, the dependence of system performance upon control techniques and, in turn, their dependence upon such information characteristics as quality, type, accuracy, and frequency is a foremost consideration for the design, implementation, performance and cost of any large, complex system.(5,6,7)

Consider vehicle headway as a performance criterion. Using current block control techniques, a minimum allowable headway, as measured in blocks, can be determined. However, using both headway position and rate control strategies, both minimum allowable headway, as measured in feet, and transient "smoothness" can be achieved with a moving block system. These control strategies, in turn, have input information requirements that can be realized by a surveillance system that includes both direct measurement techniques and estimated measures.

The integrity of the overall control system is intimately dependent upon the integrity of the communications subsystem. The determination of such system sensitivities as performance/control techniques, control techniques/information, and information characteristics/surveillance subsystem, is the required basis for control system design.

The heart of any automatic train control system, from the safety or operations viewpoint, is the train and track surveillance subsystem. The historical development of automatic train control follows, essentially, the historical development of track surveillance systems and the signaling systems to communicate commands to the train operator based on the surveillance information. The evolution of the block concept, fail-safe concept, and the vital relay were integral parts of this evolution. Continuing application of these historical principles to high speed, increasingly shorter headway, rail rapid transit systems results ultimately in shorter and shorter blocks and in a proliferation of bulky and expensive vital relays as logic trees grow increasingly complex.

The nature of the surveillance information, whether it be knowledge of block occupancy, time of transition between blocks, inference of average velocity from successive times of transition between blocks, or information from some other method, significantly affects safe train control design. Conclusions elsewhere in this report suggest the inadequacy of the fail-safe concept, by itself, and underscore the desirability of fail operational capability, with graceful degradation characteristics at the system level, and the merit of having layers of surveillance capability. An example of such a surveillance system structure is one having a minimum parts count (simple), long blocks, and a standard fail-safe components layer; a computer software "check-in-check-out" layer; and an on-board derived velocity reporting and continuously varying velocity commands layer of surveillance and control. Detailed surveillance system requirements analysis can relate such matters as new surveillance system techniques; critical system parameters such as data rate, quantization level, information type, and noise levels; electrical environment; reliability and cost; vehicle dynamics, including propulsion and braking system lags and nonlinearities; and operational requirements such as minimum headways under a variety of car load and wheel/rail conditions. Such an analysis should be done as part of the integrated, iterative process of developing both design requirements and design methodology, and methods for their verification.

6.3 CONTROL SYSTEM DESIGN VERIFICATION

The process of control system design verification is the most critical activity of the overall design process. Specifically, requirements analysis and design methodology can never be totally reliable tasks. There is always some measure of uncertainty as to the ability of a control system design and fabrication process to meet specified requirements. It is the prime objective of the verification process to ascertain the abilities and inabilities of a rail rapid transit control system. The achievement of this objective requires design iterations, rework, and a reliable measure of actual system performance prior to revenue service.

The verification process includes the following activities:

- Operational analysis
- Failure analysis
- Computer simulation

- Laboratory tests
- Prototype and pilot tests(8)
- Static subsystem tests
- Dynamic subsystem tests
- Static system tests
- Dynamic system tests and demonstrations

In order to evaluate a rail rapid transit control concept, certain analyses, computer simulations and laboratory field tests are required. Analysis is required in all phases of the performance evaluation procedure to define the performance criteria, to specify the criteria measurement procedures, and to determine system performance based upon the criterion values. Pertinent performance criteria upon which an evaluation can be based are first defined. This is done without any firm control system configuration in mind, but simply from consideration of the purpose and pertinent operational requirements of the system. These considerations include factors bearing on the purpose of the control system which is to provide safe, reliable, comfortable and efficient service to the users.

Performance criteria are of two different types. The first type are those necessary to meet minimum design constraints in order to guarantee acceptable performance. The second type are those that do not critically affect system performance, but do measure desirable performance attributes. They are therefore useful in comparing the overall performance of two candidate control concepts. Several candidate categories of performance criteria can be identified including standards of safety; control effort such as the number of computer instructions per minute of average or peak activity; levels of service; and implementational considerations.

With the performance criteria defined, an analysis of the operational environment is required in order to specify how each criterion value of a particular design concept can be measured.

In several cases, this may require the complete spectrum of analytical, computer, laboratory, and field exercises. Within each of the above categories there exists a hierarchical structure of lower level performance criteria that underlies the definition of overall performance evaluation and allows computation of the figures of merit for a candidate control system. The performance criteria have been classified above into two types: those that must meet minimum constraints, and those that can be traded off against one another. The purpose of a figure of merit computation is to provide a uniform method for evaluating the second type of criteria.

In summation, the various activities within the verification process have the collective requirement to provide the necessary and sufficient data for input to the hierarchy of performance criteria measures such that system, subsystem and control function performance can be quantitatively assessed. Documentation exists covering the individual requirements of the pertinent tasks of analyses, computer simulations and laboratory and field tests. The revenue operation of any rail rapid transit system should not be initiated until the control system design verification and system safety analysis process has been completed. A companion requirement is the proper documentation of these activities and their respective roles in the making of major design decisions.

7. POTENTIAL MECHANIZATIONS FOR FUTURE AUTOMATIC TRAIN CONTROL SYSTEMS

The operational, functional, design and implementational requirements imposed upon a rail rapid transit control system give rise to a range of possible automatic train control mechanizations. Each mechanization is dependent upon specific operational requirements and design constraints. These individual operational requirements can be minimally stated in terms of a minimum required headway or can be expanded to include the elements of cost, safety, reliability, and operational flexibility. However, without considering the degree of train control system automation, each individual automatic train control system mechanization must include the basic elements of automatic train operations, automatic train protection, automatic train supervision, and communications. These elements are defined in Section 3 and discussed in both Section 6 and Appendix D.

In general, automatic train operation pertains to unit train operation under given velocity profiles corresponding to well-defined conditions that include train, track and station characteristics. Typically, this is the innermost loop of the multi-loop, automatic train control system shown in Figure 7-1. Beyond this loop is the automatic train protection loop which, when necessary, modifies the nominal velocity profiles, employing measured changes in the system operating conditions. In essence, the automatic train protection system performs an approval function or a modification and approval function for velocity profiles requested by the automatic train supervision system.

Figure 7-1 can be considered representative of current rail rapid transit system configurations. Looking to the future, the system of Figure 7-1 can be modified by giving the automatic train supervision system the role of an active central function as depicted in Figure 7-2. In this case, the closing of the outer-most loop (dotted line of Figure 7-2) makes adaptive scheduling and control possible. It is this outer-most loop that provides the train

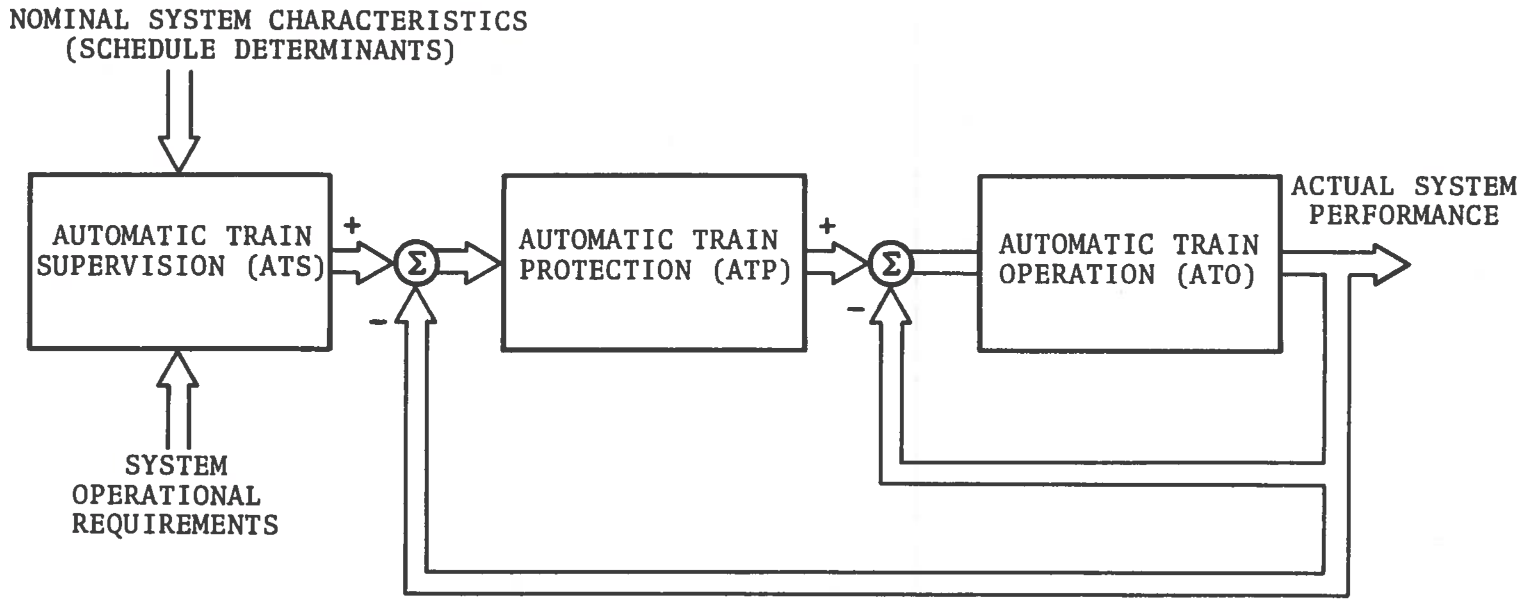


Figure 7-1 Automatic Train Supervision as an Inactive Monitor

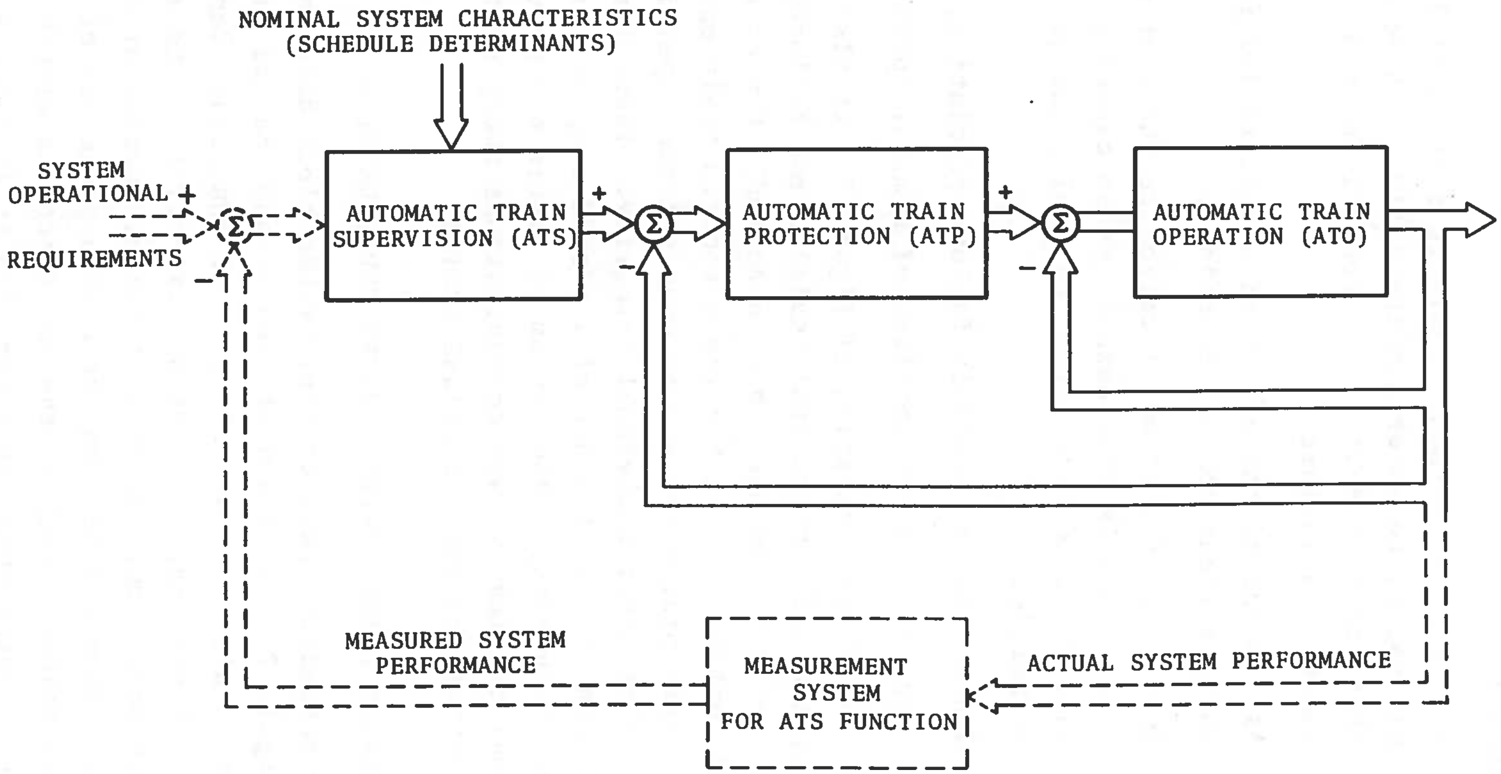


Figure 7-2 Automatic Train Supervision as an Active Control Function

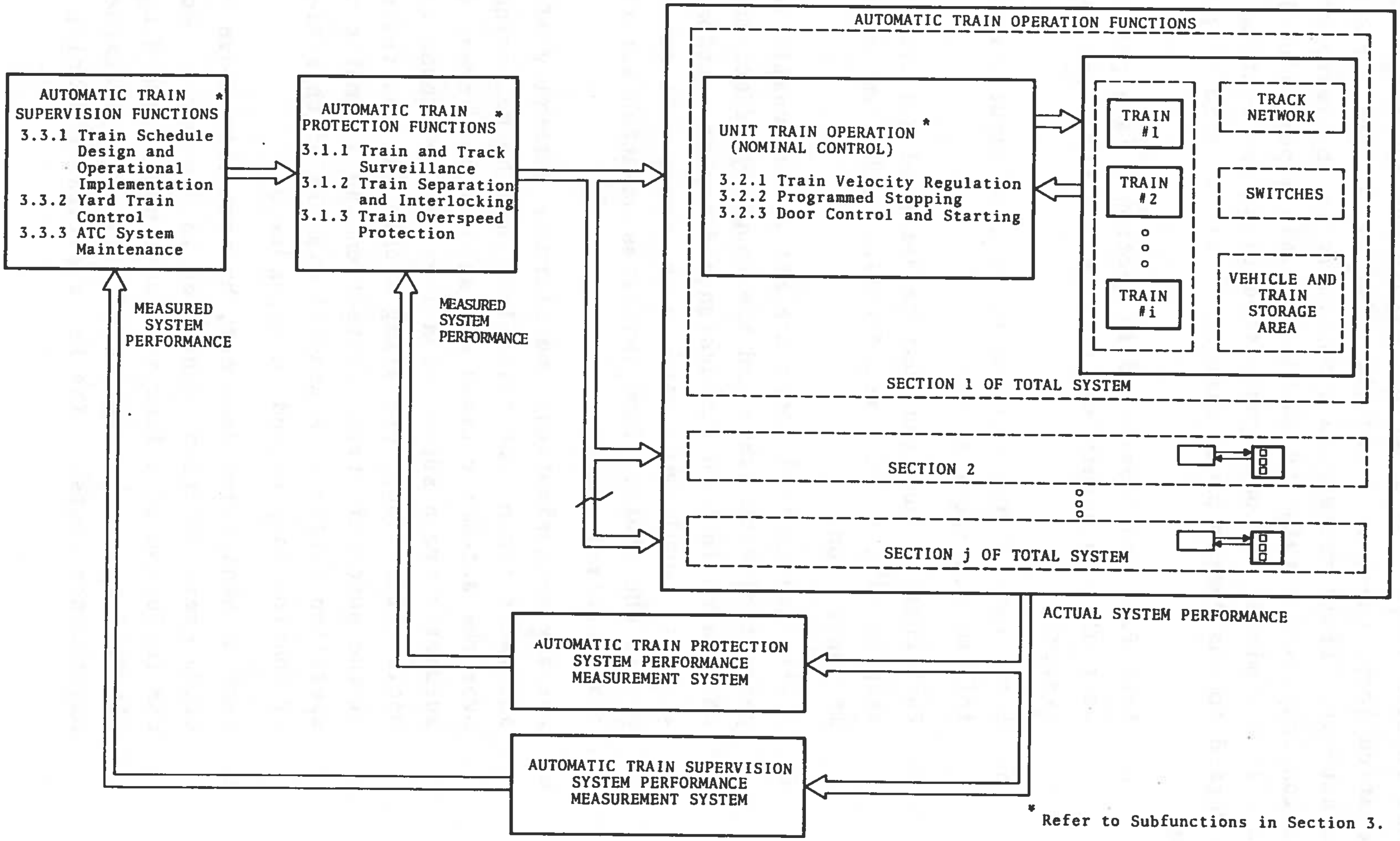
control system with the following capabilities initially treated in Section 6.1.

- Continual assessment of system status, at least minimally, to ascertain the state of those subsystems that are pertinent to any control function and to identify a failure.
- Assessment of the effect of a failure (or failures) upon the pertinent control functions.
- Selection of that modification to the control system that minimally compromises system capacity and schedule, and, of prime importance, maintains the fail-safe principle.
- Monitoring to ascertain failure resolution.
- Resumption or continuation of nominal operation.

The system representation of Figure 7-2 is also capable of maintaining the fail-operational (safe) first failure, fail-safe second failure criteria described in Appendix C provided that each individual control loop within the automatic train operation, automatic train protection and automatic train supervision functions maintains their individual integrity. These integrities are dependent upon the maintenance of a closed-loop via primary or back-up communication paths. The system of Figure 6-2 provides an example of maintaining two way communications among central, station, wayside control and the individual trains.

7.1 AUTOMATIC TRAIN CONTROL SYSTEM REPRESENTATION

The automatic train control system block diagram representation in Figure 7-3, is the next step beyond that of Figure 7-2 toward the totality of possible control functions identified in Section 3. These control functions are pertinent to automatic train operation, automatic train protection or automatic train supervision and rely on the common processes of surveillance and communications. Each of the sub-functions within the three major control loops shown in Figure 7-3 is in fact, an element of



* Refer to Subfunctions in Section 3.

Figure 7-3 Automatic Train Control System-Block Diagram other control loops. As examples, within the automatic train operation loop, there is a vehicle velocity control loop; within the automatic train protection loop, there is an overspeed protection loop; and within the automatic train supervision loop, there is a nominal and contingency scheduling and routing loop. In regard to the system block diagram it can be said in general that

a. Each function identified in Section 3 is a potential control loop within any total automatic train control system.

b. Each control loop has its respective input and output information requirements.

c. Each control function must be assigned a source of responsibility and a verification mechanism in any mechanization.

d. Individual control loops are not operationally independent of each other and the coupling effect must be considered in both the design and implementational stages. Coupling is used in the sense that activity within one control loop initiates unwanted activity in other control loops.

e. For any mechanization, the ultimate authority of the automatic train protection loop must be maintained over the automatic train operation loop whereas the automatic train supervision loop can be viewed as an optimization loop, operating within the constraints of the automatic train protection and automatic train operation systems. A general example of this hierarchy of control is provided in Appendix D.

f. Each mechanization does not, by necessity, have to include every function identified in Section 3. However, the inclusion of a function contributes toward operational flexibility at the expense of capital, operational and maintenance costs. The key questions governing the inclusion of a function are determined primarily by the operational requirements.

g. The integrity of each control loop must be maintained at all times and under all conditions in order to ensure, in the event of any failure, minimum compromise to system capacity and schedule and not going to an unsafe condition. The control loop integrity is highly dependent upon the communications system even in a back-up or degraded mode of operation.

7.2 AUTOMATIC TRAIN CONTROL SYSTEM IMPLEMENTATIONAL CONSTRAINTS

Although myriad mechanizations are possible for the family of control functions under consideration, there exist several dominant factors that govern the eventual system mechanization. They are

a. Operational Requirements - There is a clear difference in operational requirements between a high-capacity, close-headway, high speed rail rapid transit system and one having a maximum speed of the order of 30-50 mph and a minimum headway in the order of 5 minutes. The former imposes more stringent requirements upon overall control system capability and, in succession, more demanding requirements upon the total information gathering (surveillance) and processing capability.

b. Existing-System Characteristics - An excellent example of the effect of existing system characteristics upon system mechanization can be seen in the recent MBTA improvement program, using the BART system design and implementation as a comparative standard. The MBTA program was constrained by the necessity for compatability with current equipment, operational procedures and policies.[1] In contrast, the BART system offered the potential for a truly integrated design relatively free from the influence of existent hardware and operational factors.[2,3,4,5]

c. Cost - Although cost is an obvious consideration, there is an outstanding requirement to understand and know quantitatively, the relation of costs, (capital, operational and maintenance), to system configuration.

d. Accepted Techniques for Control and Surveillance - The traditional system acceptance bases of proven performance, of hardware such as fail-safe relays and track circuits for surveillance and of block control for separation assurance, can be viewed as assets. However, as operational requirements for closer headways and higher speeds develop, these assets can become constraints upon control system design and implementation.

e. Acceptance of Available Technology - Although the past two decades have produced an abundance of technological developments, the BART system is the only system design that has drawn, in any significant way, on these developments for use as active members of the automatic train operation, automatic train protection and automatic train supervision control loops. The candidate system of Appendix D and previous efforts on Personal Rapid Transit command and control systems demonstrate the potential for employing computer techniques for implementing either primary or back-up control functions.[6] Also, there are available field-proven European rail rapid transit industry relay designs that should be reviewed for application to domestic systems.(7)

7.3 CANDIDATE SYSTEMS FOR FURTHER ANALYSIS

Given the desired operational requirements of a rail rapid transit system and given a statement of implementational constraints, the family of potential system configurations becomes reasonable. However, an additional consideration beyond those identified in Section 7.2 is the physical location, or source, of the responsibility for each control loop and the monitoring of that control loop for integrity. In effect, the monitoring requirement necessitates an adaptive capability. This Section is concerned with the system configuration for the primary mode. In order to develop a configuration with adaptive capability, requirements for the automatic train operation, automatic train protection and automatic train supervision control loops must be quantified. Further, the requirements of each of the control loops of the family of subfunctions applicable to a particular system must be quantified.

An initial step toward the definition of an automatic train control system mechanization is the consideration of the distribution of basic control functions (automatic train operation, automatic train protection and automatic train supervision) and their relative positions in the hierarchy of possible locations of control responsibility, i.e., central, tower, station, wayside and vehicle. In addition, the sources of monitoring responsibility, for control loop integrity, must be specified. It is the distribution of these sources that has significant impact on system cost, operational characteristics and the maintaining of the fail operational (safe) first failure and fail-safe second failure concept described in Appendix C. The general system of Figure 6-2 can be transformed into the system of Figure 7-4, thus suggesting the possible location of control and control loop monitoring responsibility.

Given the systems of Figure 7-3 and 7-4, the family of control functions can be categorized with respect to source assignment. For a specific system, the location of some of these control function responsibilities are probably fixed and others represent a design latitude. As an example, the function of adaptive scheduling, in order to best match system capacity to system demand during off-nominal operation, will probably be done by central control and certainly not by an individual vehicle (or train) control system. Table 7-1 demonstrates a possible system configuration in terms of control function responsibility. Two points must be emphasized.

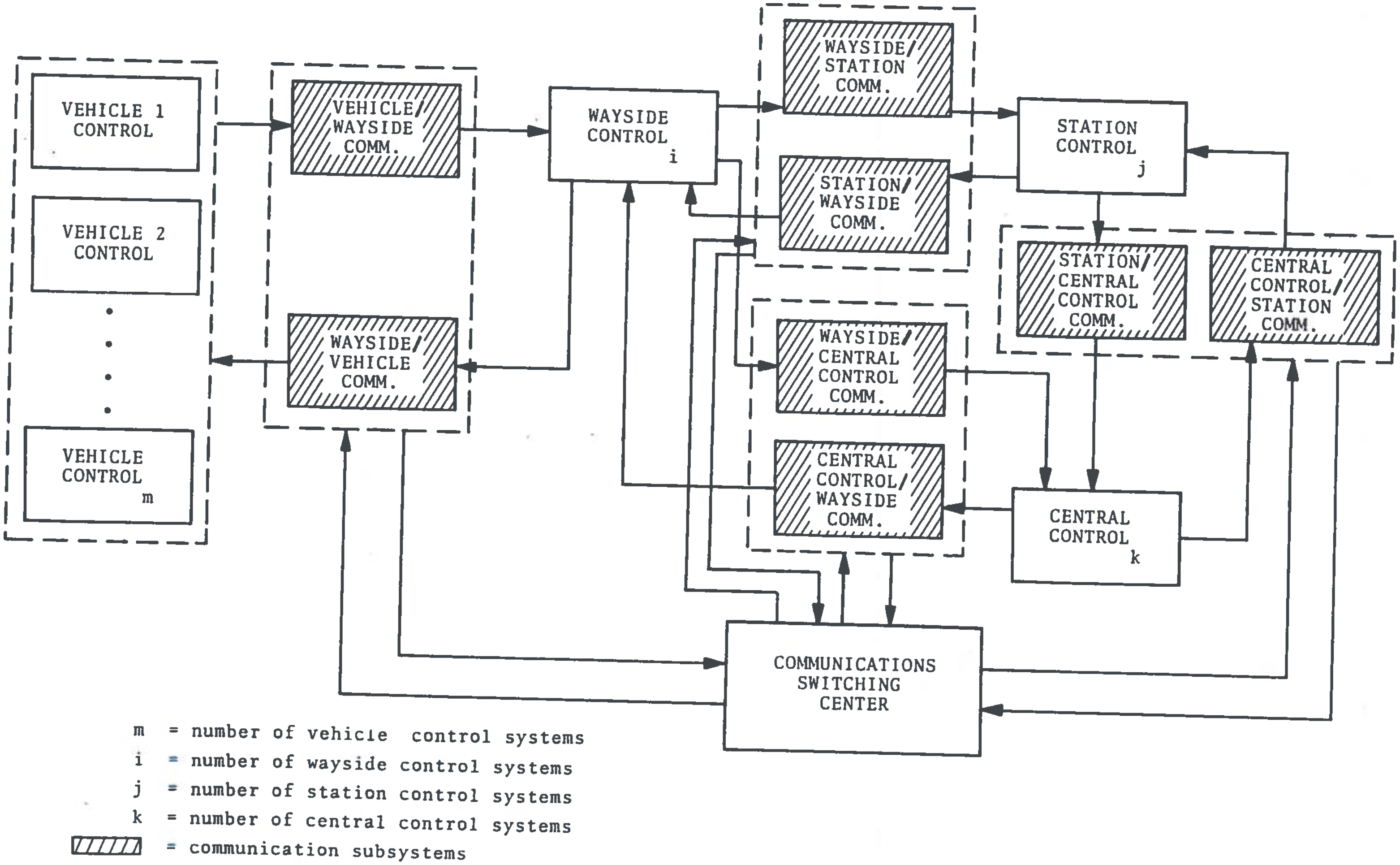


Figure 7-4 Block Diagram-Automatic Train Control System Mechanization

TABLE 7-1 EXAMPLE OF CONTROL SYSTEM FUNCTIONS ALLOCATED TO CONTROL LOCATIONS

Automatic Train Control System Function (Numbering refers to definitions in Section 3)	Control Responsibility	Monitoring Responsibility
3.1 Automatic Train Protection		
3.1.1 Train and Track Surveillance	Wayside/Station	Central/Vehicle
3.1.2 Train Separation and Interlocking	Wayside/Station	Vehicle/Central
3.1.3 Train Overspeed Protection	Vehicle	Central/Wayside
3.2 Automatic Train Operation		
3.2.1 Train Velocity Regulation	Vehicle	Wayside/Central
3.2.2 Programmed Stopping	Vehicle	Station
3.2.3 Door Control and Starting	Vehicle	Station
3.3 Automatic Train Supervision		
3.3.1 Train Schedule Design and Operational Implementation	Central	Vehicle
3.3.2 Yard Train Control	Central	Vehicle
3.3.3 Automatic Train Control System Maintenance	Central	Vehicle
3.3.4 Overall System Maintenance	Central	Vehicle
3.4 Communication System		
3.4.1 Normal System Operation Communications	Wayside	Central
3.4.2 Emergency Communications	Central	Vehicle

- Not all of the control functions listed in Table 7-1 are necessarily required in every rail rapid transit system.
- Every source of control responsibility, (central, tower, station, wayside and vehicle), does not always exist as part of a particular system configuration.

As an example, Figure 7-5 presents a derivative of Table 7-1 without any control functions residing at the wayside source. Expansion of this system into the format of the automatic train operation, automatic train protection and automatic train supervision control loops of Figure 7-3 provides a more definitive basis for specifying the system configuration as in Figure 7-6.

In summary, the subject of system configuration is a multivariable control system design problem. It has numerous and significant sensitivities among the parameters and variables of interest. The most promising path to follow in the configuration of an operational rail rapid transit control system is one of design methodology. The dominant factors of operational requirements, existing facilities, cost and accepted techniques for control and surveillance tend to diminish the number of potential configurations. The vantage point of automatic train operation, automatic train protection and automatic train supervision in accordance with Figures 7-3 and 7-4 further reduce, to a tractable number, the candidate system configurations. However, there still remains a significant degree of design latitude in terms of the distribution of control function responsibility. Associated with this design latitude are implementational and cost considerations.

Finally, the closed loop configuration of Figure 7-3 does provide an on-line adaptive capability to best match system capacity to system demand. This on-line capability should be viewed as a direct extension of available design latitude, traditionally achieved via analysis and simulation.

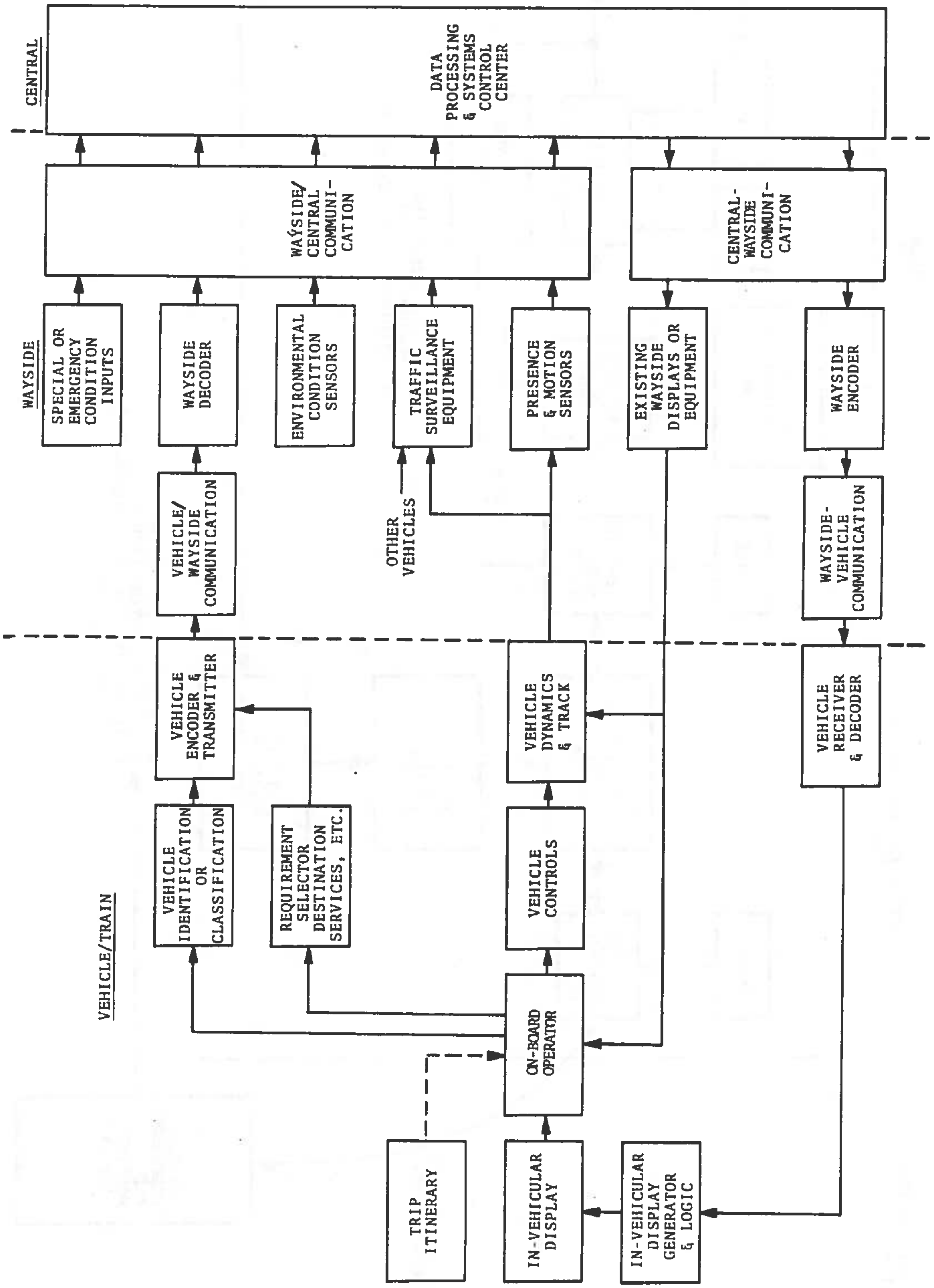


Figure 7-5 A Rail Rapid Transit System Without Wayside Control

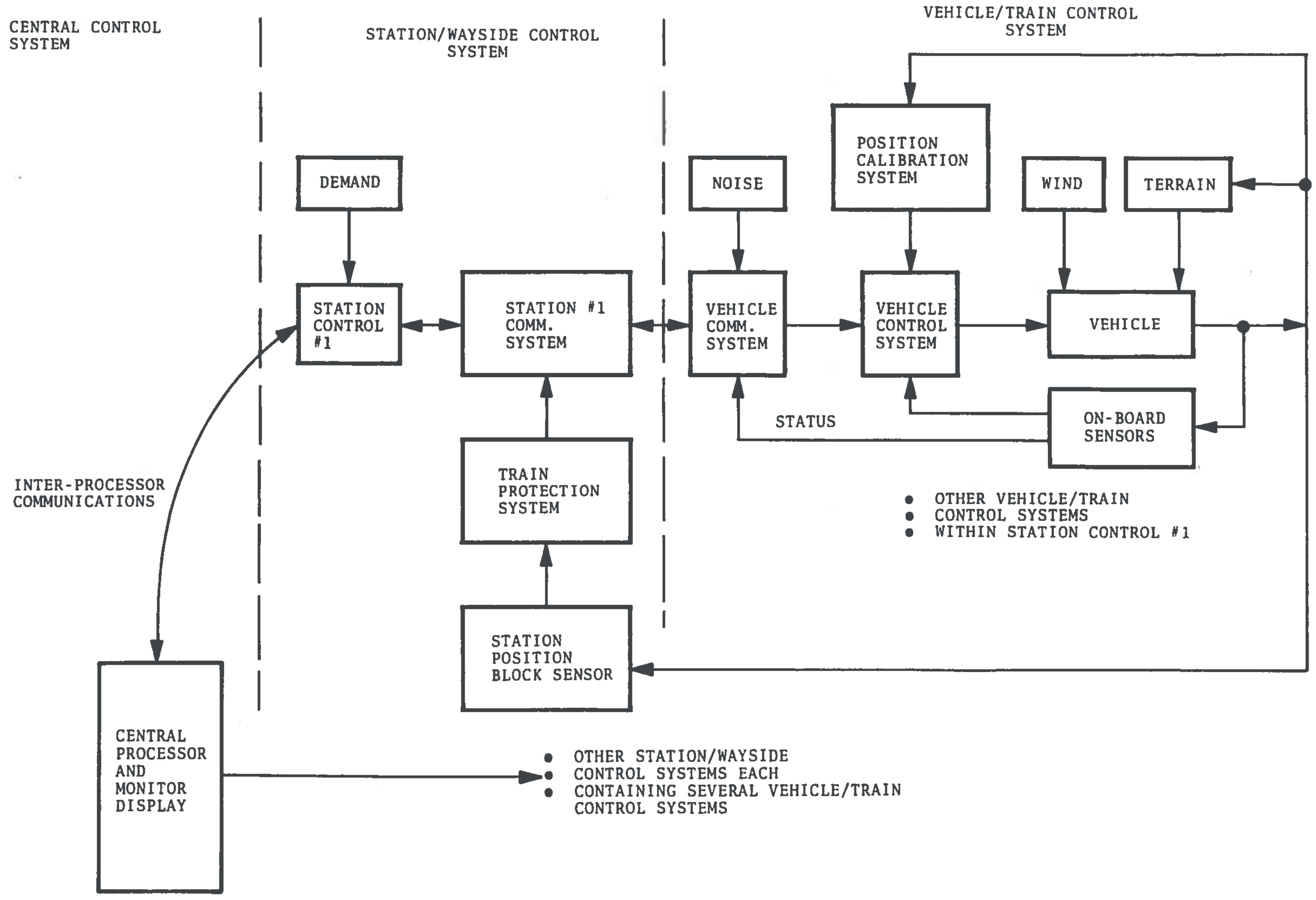


Figure 7-6 Generalized System Configuration Without Wayside Control

8. CONCLUSIONS AND RECOMMENDATIONS

This section is a compilation of conclusions and recommendations followed by supporting discussion which comprise the major findings of this Study. Most of these findings are further substantiated with related text elsewhere in the Report. This section includes specific suggestions for further work.

8.1 CONCLUSIONS

The numbered conclusions of this section have the following general topical order: safety criteria, overall safety assurance, accident statistics, train protection, train operation, train supervision, ancillary automatic functions, and a series of general overall system considerations. The titles and general topical order of corresponding conclusions, recommendations, and discussions are similar to facilitate tracing through all three aspects of one particular topic. Although the topical order is the same in all three subsections, the numbering does not track perfectly because there are some conclusions that do not have a corresponding recommendation and there are some recommendations that have more than one major element worthy of discussion.

8.1.1 Insufficient Safety Criteria to Assess Automatic Train Control System Designs

The Study found no adequate safety criteria, standards, or procedures for rail rapid transit systems, whereby automatic control system designs could be assessed with respect to safety requirements.

8.1.2 Fail-Safe Criterion Inadequate by Itself

The current principle of fail-safe design is felt to be inadequate by itself as a total system level safety criterion, a limitation upon the continuous operational capability of a rail rapid transit system and a factor inhibiting if not prohibiting new technology for system improvement with no system safety degradation.

8.1.3 Need Overall System Safety Assurance Plan

Numerous rail rapid transit safety considerations such as fire and flood are only secondarily related to the automatic train control system functions but nevertheless can significantly influence control system design decisions. An overall system safety assurance program plan is required early in the development of new systems.

8.1.4 Need Continuous Record and Analysis of Incidents, Accidents, Failures, Maintenance, and Availability Data

Safety, reliability, and maintainability are strongly linked. Records of incidents, accidents, failures, maintenance actions, etc., should be kept, analyzed, and utilized throughout the periods of development, test, rework, and particularly during the first few years of revenue service of new systems as an important part of the design verification and system improvement process.

8.1.5 Automatic Train Protection Function Should be Fully Automated

The automatic train protection function of the automatic train control system including train detection, train separation, and switching logic and control has historically been, and should continue to be, fully automated.

8.1.6 Automatic Train and Track Surveillance Systems Need More Development

The safety and operational effectiveness of a high speed, short headway rail rapid transit system cannot be any better than the surveillance system's ability to know what the trains and switches are doing. Although numerous implementation methods exist (see Appendix B), surveillance subsystems must be made more continuous, more reliable, more informative, and more independent of track layout and of the changing local track environment (electrical, mechanical, and weather) than have been demonstrated by existing systems.

8.1.7 Need Train Operator for Visual Surveillance Protection of Right-of-Way

In new rail rapid transit systems, a human operator will be required to perform as an adjunct to the train and track surveillance function unless a much higher level of exclusive right-of-way protection than has been currently achieved can be provided.

8.1.8 Degree of Train Operation Automation Still Quite Variable

Any one of several levels of train operation automation may be justified depending on factors other than technical feasibility, for example desired level of service and cost. The on-board operator should be used as an adjunct to the automatic train operation system and not just for visual surveillance and vehicle system monitoring. Precise techniques for determining the optimum level of automation and exact role of the operator in any specific system are not currently available.

8.1.9 Visual Surveillance of Door Operations is a Necessity

Visual surveillance monitoring of door operations is a necessary safety adjunct to an otherwise fully automatic function. In the absence of a conductor on long trains, such surveillance by the train operator might be supplemented by a station attendant or by television monitors

8.1.10 Properly Designed Cab

The on-board train operator should be provided with a properly designed cab to attain optimized operator performance.

8.1.11 Automated Train Supervision Functions Need Human Enhancement and Manual Backup

The majority of train supervision functions can be fully automated, but efficient operation in the event of non-normal conditions caused by equipment failures or emergencies can be significantly enhanced by human operator participation.

8.1.12 Integration of Automated Ancillary Functions with Automatic Train Control Shows Promise

Increased levels of automation in areas of rail rapid transit systems ancillary to automatic train control such as fare collection, demand counting, station gating, television monitoring for security and door operation, and automatic test of electronic equipment show promise for improving service and reducing operations and maintenance costs.

8.1.13 Automatic Train Control Expertise Important Part of Early System Planning Process

An underestimation of the importance of automatic train control expertise in the early planning process usually results in a disproportionately small percentage of capitalization costs, design effort, and management attention being allocated for the train control system as compared to that for other aspects of the total system such as right-of-way, stations, and vehicles. This error can seriously compromise the automatic train control system's inherent capabilities in the areas of safety, quality of service, recurring operational and maintenance costs, and system growth potential.

8.1.14 Need More Documentation Supporting New System Design Decisions

Automatic train control system design analysis, performance prediction, test validation planning, and justification for major design decisions should be more analytically supported and more thoroughly documented than is currently normally required by any federal or other public funding process.

8.1.15 Fully Automatic Train Control Systems Compatible with Safety

Properly designed, tested, certified, and maintained automatic train control systems have no deleterious effect upon safety. There are no inherent technological problems, but several developmental implementation problems, associated with accomplishing safe, reliable, and fully automatic train control systems of the near future.

8.1.16 Need Fuller Utilization of Design, System Integration, Test, and Rework Experience from Other Fields

Pertinent system design, test, evaluation and management methodologies and experience from other fields of modern technology have not been fully utilized in the design and implementation of new rail rapid transit systems. The complicated process of new system specification, introduction of new technology, contract management, systems integration, first article testing, systems testing, design validation and operational verification testing, rework prior to approval for revenue service and continued rework to achieve long term reliability and maintainability goals can be significantly improved for future systems by appropriate application of recent experience with this total process.

8.2 RECOMMENDATIONS

8.2.1 Develop Safety Criteria, Standards, and Procedures

Safety criteria, standards, and procedures should be developed by cooperative efforts among government, transit properties, and manufacturers and suppliers for rail transit systems to assist in the design and assessment of train control systems.

8.2.2 Develop Overall System Safety Assurance Plans

The concept of fail-safe design should be only a building block within the larger framework of an overall system safety assurance program plan tailored to each new system and encompassing treatment of all potentially hazardous situations.

8.2.3 Develop a Safety Certification Process

National rail rapid transit safety standards and guideline should be developed and should form the basis for a safety certification process for new systems.

8.2.4 Collect and Analyze Incident and Accident Data

Existing rail rapid transit incident and accident data collecting processes should be unified and upgraded to support the development of safety standards allowing safety assessment of present and proposed automatic train control systems.

8.2.5 Collect and Analyze Failure, Maintenance, Reliability, and Availability Data

New and existing rail rapid transit system data collecting and analysis processes concerning failure, maintenance, reliability, and availability should be initiated to support the development of standards allowing assessment of present and proposed automatic train control systems.

8.2.6 Develop More Continuous and More Reliable Surveillance Systems

The increasingly stringent safety and operational requirements, including higher density, higher speeds, and shorter headways, set for new rail rapid transit systems, must be met by further development of surveillance systems to make them more continuous, more reliable, more informative, and more independent of track layout and changing environment.

8.2.7 Develop Alternatives for More Effective Right-of-Way Protection

Techniques such as designing rights-of-way that are all tunnel, all elevated, better barriered at grade, or that have walls with doors separating trains and station platforms should be thoroughly evaluated as a means to improve right-of-way protection.

8.2.8 Develop Alternatives for More Effective Door Operation Surveillance

Additional study should be conducted on the interrelationships among demand analyses, station design, passenger management techniques, passenger flow in and out of vehicles, passenger distribution throughout the train, door safety devices and the need for door surveillance alternatives.

8.2.9 Follow Human Factors Design Principles for Cab Design

Cab designs for future rail rapid transit trains should follow industry and government-developed human factors design principles. These principles have been standardized and are available in a form useful for cab design.[1]

8.2.10 Develop Techniques to Determine Optimum Operator Involvement

Research on techniques for determining the optimum automation levels and degree of on-board operator involvement required in any particular rail rapid transit system should be initiated.

8.2.11 Analyze Automation of Train Supervision Functions Further

A more detailed system analysis of the train supervision functions and their communicative relationships with the train operation and train protection functions should be made to determine the trade-offs between train supervision information requirements, level of automation, implementation methods, enhancement of safety, and cost/benefit effects of initially high cost automatic equipment as compared with the recurring costs of manual operations.

8.2.12 Further Development of Automated Ancillary Functions

Potential cost savings attainable through increased application of automation to ancillary transit system functions resulting in reduced personnel requirements should be further assessed.

8.2.13 Include Safety and Automatic Train Control Expertise in Early System Planning

Appropriate system safety analysis, management, and automatic train control expertise should be an integral part of the early system planning and design process.

8.2.14 Provide Sufficient Resources for Automatic Train Control

Sufficient capitalization funding, design effort, and management attention should be allocated for development of the automatic train control system in proportion to the system's major impact on long term system safety, quality of service, recurring operations and maintenance costs, and system growth potential.

8.2.15 Require Documentation and Analysis in Support of Design Decisions

Documentation of automatic train control system design analyses, design decisions, predicted performance, and validation testing plans should be a requirement of any federal or other public funding process.

8.2.16 Develop Better Contract Management, Testing, and Rework Mechanisms

More stringent and better monitored contract management, test programs and rework mechanisms should be developed by transit authorities to verify contractor adherence to the automatic train control system safety, operational and reliability standards specified. Evidence of such a contract management philosophy and the corresponding needed technical staff capabilities, especially in the areas of safety and automatic train control expertise, should be required of a property as part of any federal or other public funding support process.

8.3 DISCUSSION

8.3.1 Safety Criteria

It was not possible for this Study to determine the precise level of safety actually being achieved on the various lines of different rail rapid transit systems as a function of different control system techniques. The Study was also not able to determine the number, nature, relative severity, and cause of accidents and their relationship to control system design. The information actually gathered in these areas was generally subjective and incomplete. There was insufficient substantive safety performance data available to determine more meaningful functional relationships among levels of safety, levels of hazard, accident types, control system design, implementation, reliability, and operational characteristics than have been presented in this report.

8.3.2 Fail-Safe Criterion

Today's primary safety criterion for any rail rapid transit system is fail-safe operation under all operational and environmental conditions. The historical development of train control techniques has led to the fail-safe principle which is defined as "a characteristic of a system which ensures that any malfunction affecting safety will cause the system to revert to a state that is generally known to be safe."

Currently, it is literally impossible to achieve fail-safe design in a large complex control system having many interacting elements and functions. As a point of interest, no organization contacted during this Study felt that they had an absolutely fail-safe system under all possible conditions. Certain subsystems can be designed in accordance with this principle and can be shown to be fail-safe. However, considering a central control facility with the many operating options available to controllers during non-normal operations, it is difficult to say that the system is fail-safe at these times. Also, during such conditions, the trains may be under manual control and the possibility exists that some safety system can be overridden or bypassed if the properly designed manual procedures are violated. Even components judged to be fail-safe with regard to all conceived failure modes occassionally fail by a mode not thought of and thereby create an unsafe condition.

Operationally, the required safe condition resulting from a malfunction is usually the shut down or drastic reduction of train operations until the failure has been ascertained and resolved. This operational principle is seldom compatible with the requirements to operate at maximum capacity and adhere to a nominal schedule. Both of these latter requirements, as well as passenger safety, are critical for an efficient, reliable mass transit system. Since it is imperative that none of these requirements should be unnessarily compromised due to a system, subsystem or component failure, the train control system should have the inherent capability to select that control system modification that yields no compromise to passenger safety and minimum compromise to system capacity, schedule, and passenger service.

Alternative means of mechanization must be considered which maintain safety while coping with failures by mechanisms other than simply stopping trains, i.e., more graceful degradation. These include redundant circuits which are self-checking, layers of independent systems which could be used at reduced levels of operation, or manual use of real-time data by a central control system. A safety system design should be developed, through implementation and prototype testing, to demonstrate that a rail rapid transit system can have a fail-operational (safe) first failure capability and fail-safe second failure capability (see Appendix C), through the use of hierarchical control systems.

The fail-safe criterion also has a restrictive effect on the application of new technology to rail rapid transit control systems. A new component development to be approved fail-safe

safe must be installed and used extensively in a system as part of the approval process. Generally, new systems only employ components already judged fail-safe. As a result of this closed, self-perpetuating process, the set of fail-safe components and their manufacturers has not changed significantly for many years. Standards and procedures must be established so that new technology, components and subsystems can be objectively evaluated and made available as designer options.

8.3.3 Overall System Safety Assurance Program Plan

Within the context of just the automatic train control system, the suggestion of fail-operational (safe) first failure and fail-safe second failure capability and use of hierarchical control in future rail rapid transit systems implies that some higher form of control system safety doctrine should be imposed, possibly including the fail-safe criterion as one of a subset of design principles.

Fire is a safety hazard which must be treated at an overall rail rapid transit system level. But it is secondarily related to the functions primarily performed by the train control system under normal circumstances. Fire on a train can best be reported via the communication subsystem of the train control system. Stopping the train at the best place for fire fighting access and passenger evacuation is linked to functions scattered throughout the total train control system. Alerting fire fighters, directing them to the scene, de-energizing third rail power, and helping the evacuation process is within the train supervision system functional capability. But passenger evacuation is obviously not just a matter of door control. Factors including number and placement of vehicle doors, steps, hand holds, door level platforms in subways, exit shaft placement, and appropriate walkways on elevated structures must be considered. These design decisions, in turn, strongly influence the door control requirements set in anticipation of fire. These types of considerations also tend to dominate system level decisions regarding the roles and proper complement of personnel required for system operation.

Passenger and transit system security is another functional area at the overall system level impacting safety considerations. It is strongly linked to operational costs but currently less so to train control functions. Extensive use of closed circuit television on trains, at doors, and in stations, however, and its integration into the communications system and door control system to assist security personnel, would have significant impact on train control system requirements.

These arguments have implications for transit management which are considered beyond the scope of this Study. Treating safety at an overall systems level rather than at the subsystem/component level should be reflected in the technical organization of the transit system. Adequate skills should be available in the organization to insure that safety requirements are fulfilled and that adequate tests or demonstrations of system safety are carried out as part of an overall system safety assurance program. The plan for such a program should be a requirement for any federal or other public funding process.

8.3.4 Safety Certification Process

The changing technology of transit vehicles, surveillance systems, and control strategies as well as changing performance requirements, dictate the need for a more comprehensive means to demonstrate and certify the safety and operational behavior of rail rapid transit systems. The projection of system operational safety and performance characteristics, historically, has been partially effected by subsystem design reviews and pre-operational testing procedures. However, the realization of system operational characteristics has been largely determined empirically during revenue operation. Validation of overall system performance, including safety, should be ascertained prior to revenue operation. This verification process should include a comprehensive design review mechanism that includes analytical studies, performance predictions, failure analyses, subsystem and system simulations under normal and non-normal operational conditions, prototype testing and field testing of the actual rail rapid transit system. The primary goal of this mechanism is to minimize any uncertainty pertinent to overall system level safety and operational behavior prior to revenue service.

Of critical importance is the simulation (both laboratory and field) of system failure events that give rise to transition between the nominal level of automated and manual operations and non-normal levels. In particular, a demonstration of the maintenance of the level of safety under potentially hazardous situations is an outstanding requirement.

There is currently a wide variation in safety demonstration requirements levied upon the various properties by different states or regulatory bodies therein. Some of these bodies accept engineering certification by the transit properties while others establish test requirements and then review and approve all test data related to safety demonstration themselves. Although details of the test procedures and methodology may still differ, depending on particular properties, a general set of requirements of guidelines could be established at the national level. This would be helpful, particularly in those cases where a system is being installed in a locality which has had no previous experience with rail rapid transit.

Nationally established broad requirements or guidelines for a system safety certification process to be carried out in detail by the appropriate state or local regulatory agency should, therefore, include a review methodology. The methodology should cover all phases of system development from conceptual planning through full schedule normal and simulated non-normal operations without passengers, prior to introduction of revenue service. Provisions should also be made for periodic retesting.

8.3.5 Incident and Accident Data

The Institute for Rapid Transit issues the "Monthly Occurrence, Accident and Injury Summary Report" which is based on separate inputs from eight major transit properties. However, the level of detailed information ideally needed for this Study was at the "single occurrence report" level and such information is generally available only from each transit property directly. A major effort beyond that of this Study would have been necessary to acquire and analyze such data. The Institute for Rapid Transit data collection process was recently established and has, therefore, a relatively short time baseline (about one year) compared to the length of statistical sample necessary for analysis of infrequent events such as collisions. The process also encompasses all types of accidents, not just those associated with automatic train control.

Since accidents are statistically infrequent events, incident, near miss, or odd occurrence reports can be extremely important mechanisms for safety improvement before reoccurrence of an incident becomes an accident. Such reports are especially valuable during the initial testing and rework periods prior to and just after beginning revenue service with a new system.

The existing incident and accident data collecting process should be upgraded to provide the information needed for requirements-related analyses. To accomplish this, standards should be developed encompassing accident and incident reporting forms, definitions of terms, categories of incidents and accidents, levels of investigation thoroughness, safety evaluation criteria, cause categories and contributing cause categories. Once gathered, the data should be used for developing safety standards, regulations, and an overall system certification process. The planning and execution of such a data gathering and analysis process should be a requirement of any federal or other public funding process.

8.3.6 Failure, Maintenance, Reliability, and Availability Data

There are very strong ties between system safety, failures, maintenance, reliability, system availability, passenger behavior, and overall transit system performance. There should be an equivalent data gathering and data analysis process for these considerations, parallel to that described for incident and accident data. Experience has shown that such an orderly process is extremely beneficial toward efficient improvement of system performance during the development, test, and early revenue service time periods. Such a process is often mandatory in order to meet reliability and availability specifications.

8.3.7 Surveillance Systems

The heart of any automatic train control system is the train and track surveillance subsystem. Automatic train control has grown with the development of both track surveillance and signalling systems which were combined to provide commands to the train operator. The block concept, fail-safe concept, vital relay concept and others were integral parts of this development. Straight forward application of these principles to higher speed and increasingly shorter headway systems typically results in shorter and shorter blocks and a non-linear proliferation of bulky and expensive vital relays as the logic element of more complex logic trees. Unfortunately, sufficient requirements analysis has not been done to determine the detailed combinations of speed, headway, block length, surveillance information type, and surveillance information quality parameters where these historically satisfactory approaches begin to break down. These approaches have also not been rigorously compared to other approaches such as using velocity information in the control logic. Such requirements analysis should be undertaken to relate new surveillance system techniques, critical system parameters, vehicle dynamics, and operational requirements. This effort should be an integral part of any system simulation, design methodology analysis, or level of automation justification effort. It would be extremely useful in any safety certification or design verification testing process.

Surveillance information significantly affects the design of safe train control as a function of individual transit property operational requirements. Consistent with other conclusions in this Section regarding the inadequacy of the fail-safe concept by itself, desire for fail-operational capability, and graceful degradation characteristics at the system level, there is merit in having layers of different types of surveillance capability. A surveillance system structure might consist of a minimum parts count (simple), long block, standard fail-safe components structure overlayed with a computer software "check in-check out" capability, and an on-board derived velocity reporting and continuously varying velocity command structure. Such alternatives should be pursued to make train detection more continuous, more reliable, and more independent of track layout and changing local track environment.

8.3.8 Right-of-Way Protection

Attempts to maintain truly exclusive right-of-way at grade or in cuts have generally been thwarted by periodic violations. It is difficult to keep trespasser vagrants out of subway tunnels, and to keep maintenance personnel, such as track walkers, alert to danger. In the absence of an on-board operator using visual surveillance to continuously verify the implicit exclusive right-of-way assumption of an otherwise fully automatic train operation system, much higher levels of right-of-way protection are required to avoid the hazards of non-normal situations, than have been currently achieved in practice.

The human operator has extensive sensory information processing and pattern recognition capabilities and can detect non-standard elements or events on the right-of-way, in most cases undetectable by any purely automatic system. Proper use of a human operator can significantly enhance overall system safety and operational effectiveness. Presence of the operator does not preclude the possibility of accidents stemming from violation of the right-of-way, but timely initiation of the emergency brake by an operator can at least reduce the possibilities and/or consequences of collision. The operator's presence is also important for coordinating possible rescue efforts and for ensuring rapid resumption of service.

An all-tunnel or all-elevated system with continuous doors and walls between the trains and station platforms might provide the desired higher levels of right-of-way protection when linked with corresponding measures at grade such as stronger vehicle retaining barriers and more effective fencing. The potential cost saving resulting from elimination of the train operator should continue to be periodically reassessed in the future and should be balanced against concomitant cost increases for required additional right-of-way protection necessary to preserve safety levels. This type of trade-off analysis should be included as part of the design methodology documentation accompanying any application for federal or other public funds. The incident data reporting and analysis process recommended earlier should also be used to verify or disprove the particular right-of-way protection design decisions made for each new system.

8.3.9 Train Operator Enhancement of Automatic Train Operations

Use of the operator solely in a vigilance mode as a visual surveillance safety monitor raises motivation problems and reduces alertness. These factors may lead to unreliable performance, intolerable in a safety monitoring task. Motivation has a profound effect on vigilance performance. Operator alertness, in general, is reduced by the low event rate experienced in service since there should be few, if any, unsafe conditions or violations of the right-of-way in a properly operating system.

Therefore, the on-board operator should be used as an adjunct to the automatic system and should have sufficient meaningful duties for motivation. For example, in order to maintain service during partial system failure he should assume the majority of the otherwise fully automated train operation functions including velocity control, control of acceleration and deceleration, positioning at the station platform and door operation. He should also operate the train during infrequent non-normal situations, such as high wind gusts, slippery track conditions, and train overloading, which constitute difficult extremes for a single automatic train control system design to handle without compromising performance during normal conditions. The opportunities for assumption of such duties should be sufficiently frequent, at least with simulators, to maintain the skill level of the operator. Responsibility for such meaningful tasks inherently aids in increasing vigilance necessary to right-of-way surveillance.

8.3.10 Door Operation Surveillance

Safe and efficient door operation requires a high level of pattern recognition for discrimination between human appendages, debris, and objects intentionally placed to block the doors. Ideally, door operation also requires human presence to discourage horseplay and to remedy doors jammed through malfunction or vandalism. Better station equipment and procedures including automatic fare collection and demand counting devices, scheduling and dwell time allocation and automatic gating can significantly reduce the door safety hazard problem, but cannot accomplish those uniquely-human capability functions mentioned above.

Use of station platform doors and walls to separate passengers from trains could minimize major passenger accidents and subsequent hazardous rescue attempts and disruptions in service. They also introduce additional problems in the event of train misalignment, door failure, or emergency evacuation of a train near a station. The extra thickness of doors and walls also make visual surveillance of door operations by the on-board operator more difficult. Television monitors may enhance the capability of a single person to survey more doors with better visibility.

8.3.11 Train Operator Cab Design

The operator's work environment must be designed and engineered, considering job functions and human factors, to aid optimum job accomplishment. Insufficient visibility, incomplete or misleading displays, unconventional or inconveniently located controls, insufficient environmental control, or a fatiguing seating position can result in degradation of operator performance below levels consistent with safety. The on-board operator should have the equipment necessary to run the train in normal service no matter which part of the automatic train operation system malfunctions. This requires appropriate status displays such as a speedometer, load meter, and air brake pressure gauges as well as displays of the train supervision system commands, such as a "go-to" speedometer. It also requires the provision of acceleration and decleration controls as well as the necessary emergency overrides. Vehicle system status indicators should also be provided as vehicle malfunction diagnostic aids in order to enhance overall system maintenance efforts and improve general system operational availability.

8.3.12 Optimum Operator Involvement

There is insufficient data at this time to determine the optimum degree of train operation automation, i.e., the best combination of man and machine, ranging up to a fully automated system with no on-board operators. System-specific parameters such as minimum design headway, station dwell time variance toleration and maximum merge rate need to be studied in relation to human capabilities by simulation and modeling of particular systems. This problem area is further complicated by considerations outside the realm of automatic train control such as the operator's possible role in passenger security and service.

8.3.13 Train Supervision Functions

The advent of large and complex rail rapid transit systems has escalated requirements for automation of train supervision functions to achieve schedule and maintenance efficiency. In view of the extensive track, station and vehicle complements of rail rapid transit systems, non-critical tasks such as routine scheduling, rescheduling, departure control, schedule maintenance, and data collection and processing for the purposes of operational bookkeeping must be automated. In addition, status monitoring of adjunct transit system elements, such as air conditioning, drain pumps, escalators, and third rail power, is amenable to automation techniques that would permit abnormal behavior of these systems to be detected and presented to train supervision personnel for evaluation and appropriate action. A more stringent requirement for automation within the automatic train supervision function arises from the operational need for on-line, real-time adaptive scheduling of non-normal transit operations. It is probably beyond the capacity of either a team of train supervision operators or a completely automatic system to perform the adaptive scheduling function to handle all possible combinations of non-normal events for certain large, complex rail rapid transit systems. However, the operator's ability to learn, remember past, similar problems, and strategize, assisted by fast time computer simulations, can be effectively applied to obtain optimum solutions to almost any such problem. The automation of the train supervision functions which are non-interfering with train protection functions and complementary to train operation functions, requires extensive computation resources. Input/output capacity and the man/machine interfaces are two major considerations for efficient interaction between the personnel and equipment of the train supervision system as well as the vehicles, and other elements of the total system.

There exists an abundance of application-oriented documentation that is addressed to control system design techniques, practices and methodologies for large, complex systems. In particular, the functional and quantitative relationships between the various subsystems and the quality of control, as measured by accepted standards of system performance, are well known. System performance depends on control techniques and they, in turn, depend on information provided to them. To understand the importance of the foregoing, consider vehicle headway as a performance criteria. Using current block control techniques, a certain minimum allowable headway, as measured in blocks, can be achieved. However, using both headway position and rate control strategies, both minimum allowable headway, as measured in seconds, and transient "smoothness" can be achieved. These control strategies have input information requirements that can be realized by a surveillance system that includes both direct measurement and estimation techniques.

8.3.14 Automated Ancillary Functions

Automatic fare collection, passenger counting, and demand scheduling; closed circuit television for security and door operation surveillance; automatic gating to reduce the door closure safety hazard and increase station dwell time consistency; and remote passenger assistance service are examples where automation technology has been used to reduce personnel requirements and consequently reduce operating costs. Integration of these capabilities with the automatic train control system can significantly affect decisions regarding the existence and/or role of on-board personnel and implementation requirements of the train supervision function, particularly the communication system. High initial investment costs for equipment and facilities to provide these capabilities and others such as automatic test equipment for rapid preventive maintenance testing and diagnostic testing, can potentially provide higher system and equipment reliability and higher overall system availability. These, in turn, can significantly reduce the typically high operations and maintenance costs of rail rapid transit systems.

8.3.15 Safety and Automatic Control Expertise in Early System Planning

Demand predictions, station spacing, train length, peak period scheduling, maximum vehicle speed, average trip time, track layout, station design, weather condition extremes, vehicle performance, equipment reliability, and numerous other important variables must be properly interrelated in the process of designing a new rail rapid transit system or extension. Because of higher priority political concerns such as bond issues, land taking, ecological impact and complicated structures problems, train control considerations in a new design tend to receive a relatively low and belated priority in view of their relative importance. The decision to merge two otherwise independent lines on common trackage for passenger convenience in deference to a two-level station, for example, has far reaching impact on control system design, and should be very carefully assessed and considered in the early, overall planning phases of system design.

The degree of independent right-of-way protection and visibility inherent in such elements as tunnels, bridges, abutments, guard rails, fences, stations, blind corners, and hill crests are the basis for early structures decisions that have tremendous impact on safety and the proper role of man in the control system; and therefore, on long term operations costs. Later system problems of insufficient storage tracks, crossovers, and yard facilities are strongly linked to early conservative track layout design, land taking, and route planning. They can cause serious operational delays, hazardous single track operations, and serious temptations to compromise safety in non-normal event control system situations.

Track layout designs inherently contain minimum headway bottlenecks typically at terminal turnaround points, merge points, and shared trackage in close-spaced downtown subway stations. New designs should include provision for long term growth at these choke points in the form of sufficient space for parallel trackage, additional station platforms, vehicle storage tracks, additional turnout positions, and oversize tunnel structures. The minimum provision should encompass acquisition of the necessary land rights, for such expansion, during system conception.

For these reasons, train control system expertise should be heavily employed early in the transit system planning and design process; more so than has historically been the case.

8.3.16 Sufficient Resources for Automatic Train Control

The initial capital costs of the train control system for a new rail rapid transit system are typically a relatively small percentage, (about three to four percent) of the total initial system cost. It is generally true that once built, a rail rapid transit system's proportionately biggest finanical problems are operation and maintenance costs and the continuous need for subsidy beyond fare box revenues.

It has also been the recent experience that complete development of the train control system to meet contracted long term reliability, maintenance, and performance specifications may involve more extensive and more expensive testing, rework, and retesting effort after starting limited revenue service than anticipated. Such delay in achieving full potential of the automatic train control system's capability might be avoided by allocating more capitalization funds, design effort and management attention resources to the development of the automatic train control system. These resources should be applied in the areas of design analysis documentation, overall system safety assurance planning, data acquisition analysis of incidents, accidents, failures, maintenance actions, and system availability. Other areas requiring attention include sufficient training of operation and maintenance personnel and provision for continuous maintenance and system improvement services through safety certification and continuing beyond initiation of full revenue service operations.

Higher initial facilities and equipment capitalization funds could also be used to lower long term maintenance costs by providing higher reliability and more cost effective operational capability, based on early control system design choices such as the quality of electronic components, simplicity of design, and utilization of automatic test equipment. Cost tradeoffs should be made to compare the benefits of higher initial facilities and equipment costs, considering the relative availability of capital versus operation and maintenance type monies.

8.3.17 Documentation and Analysis Support of Design Decisions

Rail rapid transit system planners must be convinced that analysis and documentation of tradeoffs among safety, hazard potential, implementation techniques, esthetics, operational performance, and cost are possible to achieve. Efforts must be made to better define and measure the more important of these interrelationships in parallel with the other recommendations in order to quantify incident and accident statistics, justify control system design decisions, and perform top level system parameter tradeoffs. Early economic analysis of the cost impact of control system decisions must similarly be done to justify train control systems which are able to achieve high levels of system safety, minimize recurring operations and maintenance costs, ease system start-up problems, and provide cushion capacity for future growth. Documentation of these tradeoffs and all major design decision rationale should be required as part of any federal or other public funding process.

One way to help accomplish this is to develop and demonstrate a simulation model which incorporates all the key system parameters as variables, models predicted system operational and safety performance, and relates critical design parameters to major design decisions. Such a simulation could be used in the detailed design and verification testing phases of system development and as an important part of the system safety certification process.

The Study found little substantiated information justifying fully automatic train control on new systems. This is not to say that automatic train control is not needed or is not basically justifiable. The underlying justification is, of course, the intuitive conclusion that an automated system should be more economical than a man-operated system in achieving or surpassing a given level of service and safety. Formal analyses are necessary to provide better information on overall reliability requirements of automatic train control and enable better procurement practices for equipment. Such analyses might also indicate needs for different types of financial terms which would provide long-term responsibility by the supplier for control system performance.

Although there has been an historical trend toward upgrading existing systems to higher levels of automation of the train control functions, the Study also found little formal rationale to support such expenditures nor empirical data gathered after the change and based on measurable safety, economic, or operational factors to substantiate such decisions. As a result, there is currently little substantive data or design methodology for aiding future design decisions on train control systems, extensions or upgradings.

The gathering of quantitiative data before and after automation level changes in existing control systems should be encouraged in order to provide a data base for developing improvements to other systems. This process should be tied closely to analysis and documentation of safety level predictions and to an incident and accident data collection and analysis activity as part of the verification testing process.

Another area where careful analysis and documentation of design decisions is needed concerns safety level and cost tradeoffs. In theory, it is generally agreed that the safety level of rail rapid transit systems should be as high as possible and should not be compromised by cost. In practice, however, such tradeoffs are made, masked by the inability to quantitatively relate safety level prediction, safety hazard potential, train control equipment reliability, and accident statistics. For example, use of station platform doors and walls to separate passengers from the trains could minimize major passenger accidents and subsequent hazardous rescue attempts and disruptions in service. However, such doors are expensive, introduce esthetic considerations, introduce difficult requirements on train control stopping performance, and lead to the need for equivalent right-of-way protection everywhere on the system. The degree of exclusive right-of-way protection elsewhere in the system is also directly linked to level of safety and cost. Tunneling minimizes right-of-way violation but is more expensive than at-grade trackage. Strong, high guard rails between tracks and between trackage and adjacent roads are safer but more expensive and esthetically less pleasing than lesser barriers.

More effort must be made to formally analyze and document these types of tradeoffs to benefit development of future systems.

8.3.18 Automatic Train Control Compatible with Safety

A major objective of this Study was to assess the potential impact of automatic train control on rail rapid transit system safety. The detailed functional requirements for a typical rail rapid transit system were developed as part of this Study and are contained in Chapter 3. Various existing systems (summarized in Appendix A), their inherent level of technology, and the available, although not applied, technology were reviewed and compared with these functional requirements. No contra-indications, vis-a-vis safety were determined to the application of such technology to train control. Fully automatic train control was considered to be only an extension of current levels of automation. Note that a fully automatic system does not preclude the possibility of a human in the cab, at the central control facility or elsewhere in the system.

The basic train protection systems in general use are automated almost universally although an on-board operator may be used to slow or stop the train in response to safety commands rather than subjecting passengers to emergency-stop deceleration. Train operation systems, e.g., starting, velocity control, station stopping, and door operation, are done automatically, in whole or in part, in many transit systems. Traffic supervision is the function that has the least degree of automation to date but there are no fundamental technical limitations precluding full automation of this function.

Equipment failures in the automatic system and subsequent attempts to continue revenue service in a non-normal operational mode may result in special safety problem situations. Special procedures are required to ensure that such non-normal operation cannot bypass or override any safety system. These same procedures must also ensure minimum time exposure of passengers and system personnel to any increased hazard.

8.3.19 Better Contract Management, System Integration, Testing, and Rework Mechanisms

The specification of a new rail rapid transit system, introduction of new technology, contract management, systems integration, first article testing, systems testing, design verification and operational verification testing, rework, safety certification prior to approval for revenue service, and continued rework to achieve long term reliability, maintainability, and system availability goals are difficult tasks. Every effort, therefore, should be made to utilize related experience from other fields of modern technology.

The Manned Space Flight program has many examples where complicated systems were developed which involved a high degree of safety consciousness. The preponderance of the safety program was placed on two major post-design activities: determination of failure modes and effects analysis. This analysis consisted of a continuous systematic evaluation of the in-being system design. Each component and each human function were considered individually as to the consequences of possible failure. When it could be shown that a potentially dangerous situation could result from a single failure, appropriate design modifications were initiated. The other activiity consisted of a rigid systematic program to explain all failures encountered from the earliest phases of component testing on through to final operational testing. Whenever a failure occurred, it was immediately logged and a sequence of corrective actions was initiated. A special group was established to ensure that all failures had been properly closed out prior to manned operations. An enormous amount of applicable contract management, system integration, and testing experience exists as a result of these activities.

Control system design methodology alternatives should be developed for rail rapid transit systems that would make more extensive use of available and proven control system design techniques and practices. The control system should be considered as a multi-loop, closed-loop feedback control system that must maintain its integrity at all times; in no way compromising safety, and, in case of failure, minimally compromising system performance.

Better specification standards for the design, prediction of performance, procurement, implementation, and test of rail rapid transit control systems should be developed. Performance and functional specifications provide a tool for insuring subsystem compatability, an especially critical matter when different suppliers are providing different subsystems. Such specifications would include a quantitative definition of interface requirements to be authenticated early in the design of the rail rapid transit control system. An underlying requirement is the critical level of engineering skill required to be resident within a transit authority, to ensure successful generation and maintenance of such specifications and to successfully achieve integration of the train control system with the vehicle, track network, power distribution, maintenance, and other interfacing systems.

APPENDIX A

SUMMARY CHARACTERISTICS OF EXISTING AND PROPOSED RAIL RAPID TRANSIT SYSTEMS

Table A-1 summarizes several characteristics of the most automated lines of representative rail rapid transit systems. The Table entries correspond either to the currently operational situation of the line or the intended capability of those lines currently in partial operation or under construction. The information was gathered from personal visits, telephone conversations, written questionnaires, system specifications, and brochures. Considerable editing was necessary to transform the raw information from these sources into the Table entries. A blank entry means that sufficiently detailed information was not readily available at the time of publication to warrant inclusion.

TABLE A-1 SUMMARY CHARACTERISTICS OF EXISTING AND PROPOSED RAIL RAPID TRANSIT SYSTEMS (Sheet 1 of 14)

VEHICLES

SYSTEM CHARACTERISTICS MOST AUTOMATED LINE OF TRANSIT AUTHORITY	TYPES/ DESCRIPTION	TRAIN COMPOSITION, PEAK OPERATION (NUMBER OF CARS)	MANUFACTURER	LENGTH OF SERVICE (YEARS) OR EXPECTED DELIVERY DATE
BAY AREA RAPID TRANSIT DISTRICT (BARTD) ALL LINES PARTIALLY OPERATIONAL	A & B TYPE CARS	10 FOR PEAK (4-7 CURRENTLY) A'S AT FRONT & BACK B'S BETWEEN	ROHR CORP.	2
CHICAGO TRANSIT AUTHORITY (CTA) LAKE - DAN RYAN LINE	A & B TYPE CARS (2200 SERIES)	8 (4 MARRIED PAIRS)	BUDD	3-4
MASSACHUSETTS BAY TRANSPORTATION AUTHORITY (MBTA) RED LINE PARTIALLY OPERATIONAL	A & B TYPE CARS 2 DIFFERENT GROUPS	4 (2 MARRIED PAIRS)	PULLMAN-STANDARD	4
MUNICH METRO WEST GERMANY				
NEW YORK CITY TRANSIT AUTHORITY (NYCTA) SECOND AVENUE LINE UNDER CONSTRUCTION	A & B TYPE CARS R-44 R-46	8 A, B, B, A, A, B, B, A.	ST. LOUIS CAR (R-44) PULLMAN-STANDARD (R-46)	3 (R-44) 1974 (R-46)
PORT AUTHORITY TRANSIT CORPORATION (PATCO)	25 SINGLE CARS 25 DOUBLE SETS	6 FOR PEAK 2 FOR OFF PEAK SINGLES FOR LOW VOLUME HOURS	BUDD	4
SISTEMA DE TRANSPORTE COLECTIVO (STC) MEXICO CITY LINE #1, #2, AND #3	TYPE M, CAB CARS WITH MOTORS TYPE R, TRAILER CARS TYPE N, MOTOR CARS	ALWAYS 2 M, 3 R and 4 N	BRISSONEAU ET LOTS (FRANCE)	3
WASHINGTON METROPOLITAN AREA TRANSIT AUTHORITY (WMATA) UNDER CONSTRUCTION	A & B TYPE CARS	8 (4 MARRIED PAIRS)	ROHR CORP.	1974

TABLE A-1 SUMMARY CHARACTERISTICS OF EXISTING AND PROPOSED RAIL RAPID TRANSIT SYSTEMS (Sheet 2 of 14)

VEHICLES

SYSTEM CHARACTERISTICS / MOST AUTOMATED LINE OF TRANSIT AUTHORITY	TESTING AND MAINTENANCE FREQUENCY (MILES)	PASSENGER CAPACITY (NUMBER OF PEOPLE)		
		SEATED	FULL LOAD	CRUSH LOAD
BAY AREA RAPID TRANSIT DISTRICT (BARTD) ALL LINES PARTIALLY OPERATIONAL	EACH CAR PERFORMANCE CHECKED IN YARD BEFORE ENTERING REVENUE SERVICE.	72	120	212
CHICAGO TRANSIT AUTHORITY (CTA) LAKE - DAN RYAN LINE		A CAR, 47 B CAR, 51	75	100
MASSACHUSETTS BAY TRANSPORTATION AUTHORITY (MBTA) RED LINE PARTIALLY OPERATIONAL	5000	64	175	239
MUNICH METRO WEST GERMANY				
NEW YORK CITY TRANSIT AUTHORITY (NYCTA) SECOND AVENUE LINE UNDER CONSTRUCTION	7000	A CAR, 70 B CAR, 76	115	350
PORT AUTHORITY TRANSIT CORPORATION (PATCO)	4 LEVELS: A = 12,000 B = 36,000 C = 72,000 D = 240,000	SINGLES 72 DOUBLES 160	SINGLES 105 DOUBLES 240	200 PER CAR
SISTEMA DE TRANSPORTE COLECTIVO (STC) MEXICO CITY LINE #1, #2, AND #3	3,700-5,000	M CAR, 38 N CAR, 39 R CAR, 39	M CAR, 132 N CAR, 131 R CAR, 131	170 PER CAR
WASHINGTON METROPOLITAN AREA TRANSIT AUTHORITY (WMATA) UNDER CONSTRUCTION	10,000	80	175	240

TABLE A-1 SUMMARY CHARACTERISTICS OF EXISTING AND PROPOSED RAIL RAPID TRANSIT SYSTEMS (Sheet 3 of 14)

VEHICLES

SYSTEM CHARACTERISTICS MOST AUTOMATED LINE OF TRANSIT AUTHORITY	SERVICE ACCELERATION (MPH/SEC)	SERVICE DECELERATION (MPH/SEC)	EMERGENCY DECELERATION (MPH/SEC)	SERVICE JERK LIMITS (MPH/SEC^2)	EMERGENCY JERK LIMITS (MPH/SEC^2)
BAY AREA RAPID TRANSIT DISTRICT (BARTD) ALL LINES PARTIALLY OPERATIONAL	2.5	3.0	3.0	1.0	1.0
CHICAGO TRANSIT AUTHORITY (CTA) LAKE - DAN RYAN LINE	3 LEVELS: 1.0 2.0 3.0	3 LEVELS: 1.0 2.0 3.0	3.0 DYNAMIC 3.0 DISC 2.0 MAGNETIC		
MASSACHUSETTS BAY TRANSPORTATION AUTHORITY (MBTA) RED LINE PARTIALLY OPERATIONAL	2.50	2.75	3.25	3.00	4.00
MUNICH METRO WEST GERMANY					
NEW YORK CITY TRANSIT AUTHORITY (NYCTA) SECOND AVENUE LINE UNDER CONSTRUCTION	2.5	3.0 BELOW 50 MPH 2.5 ABOVE 50 MPH DROPS TO 2.3 AT 80 MPH	3.2 BELOW 40 MPH 3.0 ABOVE 40 MPH DROPS TO 2.4 AT 80 MPH	.75	NONE
PORT AUTHORITY TRANSIT CORPORATION (PATCO)	3.0	2.5 DYNAMIC 3.0 AIR	3.2 BELOW 50 MPH 2.5 AT 75 MPH	2.0 STOPPING 3.0 STARTING	
SISTEMA DE TRANSPORTE COLECTIVO (STC) MEXICO CITY LINE #1, #2, AND #3	2.9	4.0	4.5		
WASHINGTON METROPOLITAN AREA TRANSIT AUTHORITY (WMATA) UNDER CONSTRUCTION	3.0	5 LEVELS: .75 1.8 2.0 2.2 3.0	3.2		

TABLE A-1 SUMMARY CHARACTERISTICS OF EXISTING AND PROPOSED RAIL RAPID TRANSIT SYSTEMS (Sheet 4 of 14)

VEHICLES

SYSTEM CHARACTERISTICS MOST AUTOMATED LINE OF TRANSIT AUTHORITY	WHEEL TYPE AND BRAKE TYPE	BRAKE TYPE DOWN TO VELOCITY (MPH)	SLIP SLIDE CONTROL?	DOOR INTERLOCKS
BAY AREA RAPID TRANSIT DISTRICT (BARTD) **ALL LINES PARTIALLY OPERATIONAL**	STEEL RIM ALUMINUM HUB STEEL AXLE	DYNAMIC TO 10, THEN DISK TO 0.	YES	INTERLOCKED WITH MOTION RELAY AND UNDER STATION AND CENTRAL AUTOMATIC CONTROL.
CHICAGO TRANSIT AUTHORITY (CTA) **LAKE - DAN RYAN LINE**	STEEL	DYNAMIC TO 5, THEN DISK TO 0.	NO. CONSIDERED TO DEGRADE OPERATOR CONTROL.	DOOR CLOSURE INTERLOCKED WITH POWER; BYPASS POSSIBLE AT ANY SPEED.
MASSACHUSETTS BAY TRANSPORTATION AUTHORITY (MBTA) **RED LINE PARTIALLY OPERATIONAL**	STEEL	DYNAMIC THEN AIR OPERATED TREAD.	CONTINUOUS EXCEPT IN EMERGENCY.	MOTION DETECTION SYSTEM PROHIBITS DOOR OPENING.
MUNICH METRO WEST GERMANY				
NEW YORK CITY TRANSIT AUTHORITY (NYCTA) **SECOND AVENUE LINE UNDER CONSTRUCTION**	STEEL WHEELS COMPOSITE BRAKE SHOES.	SERVICE-DYNAMIC BLENDED WITH AIR EMERGENCY-AIR.	YES. FOR SERVICE BRAKING ONLY.	MOTION DETECTION SYSTEM PREVENTS DOOR OPENING. NO POWER AVAILABLE WHEN DOORS ARE OPEN. BYPASS AVAILABLE.
PORT AUTHORITY TRANSIT CORPORATION (PATCO)	WHEEL-STEEL BRAKE-COMPOSITE SHOES AND TREAD.	DYNAMIC TO 5-12, THEN AIR FROM 15 to 0. (WABCO-RT-5)	AIR LOAD SUSPENSION ADJUSTS LOAD SPRING AND CONTROLS SLIP SLIDE ELECTRONICS.	"NO MOTION" RELAY DROPS OUT AT 3 MPH AND INTERLOCKS WITH DOOR OPEN SWITCH. IF DOOR OPENS TRAIN STOPS. VAPOR CORP. TYPE.
SISTEMA DE TRANSPORTE COLECTIVO (STC) **MEXICO CITY** **LINE #1, #2, AND #3**	RUBBER TIRES SUPPLEMENTED WITH STEEL SAFETY WHEELS.	DYNAMIC TO 7.5 MPH THEN WOOD BRAKE SHOES APPLIED ON STEEL WHEELS TO FULL STOP.	NO.	INTERLOCKED PNEUMATICALLY AND CAN'T BE OPENED WHEN TRAIN IS MOVING, EXCEPT WITH A SPECIAL COMMAND OF THE OPERATOR. CAN ACCELERATE TO 3.3 MPH FROM STOP WITH PARTIAL DOOR CLOSURE.
WASHINGTON METROPOLITAN AREA TRANSIT AUTHORITY (WMATA) **UNDER CONSTRUCTION**	STEEL	CYLINDRICAL STRESS, DISC.		"NO MOTION" RELAY USED; NO POWER AVAILABLE WHEN DOORS ARE OPEN.

TABLE A-1 SUMMARY CHARACTERISTICS OF EXISTING AND PROPOSED RAIL RAPID TRANSIT SYSTEMS (Sheet 5 of 14)

TRACK AND STATIONS

SYSTEM CHARACTERISTICS / MOST AUTOMATED LINE OF TRANSIT AUTHORITY	NUMBER AND TYPES OF STATIONS	LENGTH OF LOADING PLATFORM		STATION SEPARATION	
		MINIMUM (FEET)	MAXIMUM (FEET)	MINIMUM (MILES)	MAXIMUM (MILES)
BAY AREA RAPID TRANSIT DISTRICT (BARTD) ALL LINES PARTIALLY OPERATIONAL	6 SURFACE 14 ELEVATED 14 SUBWAY	700	700	.35	5.85
CHICAGO TRANSIT AUTHORITY (CTA) LAKE - DAN RYAN LINE	27 TOTAL	420 (FOR 8 CARS)	ADJOINING "LOOP" STATION PLATFORMS.		
MASSACHUSETTS BAY TRANSPORTATION AUTHORITY (MBTA) RED LINE PARTIALLY OPERATIONAL	17 TOTAL 8 SUBWAY	440	487	.80	1.27
MUNICH METRO WEST GERMANY					
NEW YORK CITY TRANSIT AUTHORITY (NYCTA) SECOND AVENUE LINE UNDER CONSTRUCTION	2 SURFACE 19 SUBWAY	640	1000	.35	2.0
PORT AUTHORITY TRANSIT CORPORATION (PATCO)	5 ELEVATED 7 SUBSURFACE	420	560	.19	3.20
SISTEMA DE TRANSPORTE COLECTIVO (STC) MEXICO CITY LINE #1, #2, AND #3	22 LINE #1 (1 SURFACE) 19 LINE #2 (10 SURFACE) 7 LINE #3	490 (ALL LINES)	575 (LINE #2)	.25 (LINE #3)	.92 (LINE #2)
WASHINGTON METROPOLITAN AREA TRANSIT AUTHORITY (WMATA) UNDER CONSTRUCTION	86 TOTAL 48 SUBSURFACE	600		.28	2.80

TABLE A-1 SUMMARY CHARACTERISTICS OF EXISTING AND PROPOSED RAIL RAPID TRANSIT SYSTEMS (Sheet 6 of 14)

TRACK AND STATIONS

SYSTEM CHARACTERISTICS / MOST AUTOMATED LINE OF TRANSIT AUTHORITY	RAIL CONNECTION	MAXIMUM GRADE (%)	BLOCK LENGTH	
			MINIMUM (FEET)	MAXIMUM (FEET)
BAY AREA RAPID TRANSIT DISTRICT (BARTD) ALL LINES PARTIALLY OPERATIONAL	CONTINUOUSLY WELDED EXCEPT BOLTED AT SWITCHES.	4.0	75	1100
CHICAGO TRANSIT AUTHORITY (CTA) LAKE - DAN RYAN LINE	CONTINUOUSLY WELDED; WELDED AND BOLTED.	4.2	300	2,000
MASSACHUSETTS BAY TRANSPORTATION AUTHORITY (MBTA) RED LINE PARTIALLY OPERATIONAL	PREDOMINANTLY WELDED RAIL WITH CROSSOVER AREAS BOLTED.	3.0	425	2,100
MUNICH METRO WEST GERMANY				
NEW YORK CITY TRANSIT AUTHORITY (NYCTA) SECOND AVENUE LINE UNDER CONSTRUCTION	CONTINUOUSLY WELDED.	4.6	100	2000
PORT AUTHORITY TRANSIT CORPORATION (PATCO)	NEW RAIL. CONTINUOUSLY WELDED, OLD RAIL AND SWITCHES BOLTED.	5.0	295	3400
SISTEMA DE TRANSPORTE COLECTIVO (STC) MEXICO CITY LINE #1, #2, AND #3	COMBINATION OF CONTINUOUSLY WELDED AND BOLTED.	7 (LINE #1)	62 (LINE #1)	1810 (LINE #2)
WASHINGTON METROPOLITAN AREA TRANSIT AUTHORITY (WMATA) UNDER CONSTRUCTION	CONTINUOUSLY WELDED.	4.0	50	LESS THAN 2,000.

TABLE A-1 SUMMARY CHARACTERISTICS OF EXISTING AND PROPOSED RAIL RAPID TRANSIT SYSTEMS (Sheet 7 of 14)

TRACK AND STATIONS

SYSTEM CHARACTERISTICS / MOST AUTOMATED LINE OF TRANSIT AUTHORITY	TRAIN CONTROL EQUIPMENT	HEADWAY		
		SPECIFIED (SEC)	ACHIEVED (SEC)	PROJECTED (SEC)
BAY AREA RAPID TRANSIT DISTRICT (BARTD) ALL LINES PARTIALLY OPERATIONAL	WESTINGHOUSE ELECTRIC	90	600	120
CHICAGO TRANSIT AUTHORITY (CTA) LAKE - DAN RYAN LINE	GENERAL RAILWAY SIGNAL COMPANY (GRS) AND WESTINGHOUSE AIR BRAKE CO. (WABCO)	120	120	
MASSACHUSETTS BAY TRANSPORTATION AUTHORITY (MBTA) RED LINE PARTIALLY OPERATIONAL	GRS		240	
MUNICH METRO WEST GERMANY	SIEMENS			
NEW YORK CITY TRANSIT AUTHORITY (NYCTA) SECOND AVENUE LINE UNDER CONSTRUCTION	R-44 GRS R-46 WABCO	90		90
PORT AUTHORITY TRANSIT CORPORATION (PATCO)	WABCO	120	120 BEHIND EXPRESSES.	
SISTEMA DE TRANSPORTE COLECTIVO (STC) MEXICO CITY LINE #1, #2, AND #3		145	110	90
WASHINGTON METROPOLITAN AREA TRANSIT AUTHORITY (WMATA) UNDER CONSTRUCTION	GRS	120		85

TABLE A-1 SUMMARY CHARACTERISTICS OF EXISTING AND PROPOSED RAIL RAPID TRANSIT SYSTEMS (Sheet 8 of 14)

TRACK AND STATIONS

SYSTEM CHARACTERISTICS / MOST AUTOMATED LINE OF TRANSIT AUTHORITY	TRAIN VELOCITY		STATION DWELL TIME	STATION BYPASS CAPABILITY AND CRITERIA
	MAXIMUM ALLOWED (MPH)	OPERATIONALLY EXPERIENCED (MPH)	NOMINAL (SEC) MINIMUM (SEC) MAXIMUM (SEC)	
BAY AREA RAPID TRANSIT DISTRICT (BARTD) ALL LINES PARTIALLY OPERATIONAL	80	80	10 5 20-40	CAPABILITY FOR RUN-THROUGH MANUALLY USED ONLY FOR MAINTENANCE.
CHICAGO TRANSIT AUTHORITY (CTA) LAKE - DAN RYAN LINE	70	55	—— 20	YES FUNCTION OF STATION DEMAND.
MASSACHUSETTS BAY TRANSPORTATION AUTHORITY (MBTA) RED LINE PARTIALLY OPERATIONAL	70	50	15 10 30	YES CAN DISPATCH SHORT RUN EXPRESS TO MAKE UP SCHEDULE.
MUNICH METRO WEST GERMANY				
NEW YORK CITY TRANSIT AUTHORITY (NYCTA) SECOND AVENUE LINE UNDER CONSTRUCTION	70		30 15 45	YES, SCHEDULED SKIP STATION OPERATION IN PEAK HOURS.
PORT AUTHORITY TRANSIT CORPORATION (PATCO)	75	75	20 11 90 (CRUSH LOAD)	NORMAL OPERATIONS SCHEDULE USES EXPRESS AND SHORT RUN TRAINS. TOWER MAY DIRECT A STATION BY-PASS IN ORDER TO MAINTAIN SCHEDULE OF RELIEVE PASSENGER CONGESTION.
SISTEMA DE TRANSPORTE COLECTIVO (STC) MEXICO CITY LINE #1, #2, AND #3	50	45	17 11 30	TRAINS NORMALLY STOP AT ALL STATIONS.
WASHINGTON METROPOLITAN AREA TRANSIT AUTHORITY (WMATA) UNDER CONSTRUCTION	80 (DESIGN)	75 (PROJECTED)	20 15 ——	YES SKIP STATION CONTROL FUNCTION BASED ON DEMAND AND SCHEDULE STATUS.

TABLE A-1 SUMMARY CHARACTERISTICS OF EXISTING AND PROPOSED RAIL RAPID TRANSIT SYSTEMS (Sheet 9 of 14)

SYSTEMS

SYSTEM CHARACTERISTICS MOST AUTOMATED LINE OF TRANSIT AUTHORITY	AVERAGE RUN SPEED (MPH)	POSITIVE INDICATION OF SWITCH POSITION	INDICATION TYPE AVAILABILITY	FAULTY SWITCH DETECTION TECHNIQUE
BAY AREA RAPID TRANSIT DISTRICT (BARTD) ALL LINES PARTIALLY OPERATIONAL	47	SWITCH POSITION SENSORS CONTROL LIGHTS ON CENTRAL PANEL. BACK-UP ON ILLUMINATED KEY LOCKED STATION CONTROL PANEL.	ROUTE MAP LIGHTS INDICATE SWITCH POSITION AT CENTRAL AND STATION CONTROL.	
CHICAGO TRANSIT AUTHORITY (CTA) LAKE - DAN RYAN LINE	30	YES	AVAILABLE TO TRAIN OPERATOR, TOWERS; RECORDED AS VITAL DATA.	DAILY VISUAL INSPECTION.
MASSACHUSETTS BAY TRANSPORTATION AUTHORITY (MBTA) RED LINE PARTIALLY OPERATIONAL	32	YES		FAIL-SAFE CIRCUITRY, RELAY LOGIC; VISIBLE INSPECTION.
MUNICH METRO WEST GERMANY		SIGNAL ASPECT IS GOVERNED DIRECTLY THROUGH SWITCH POSITION TO INDICATE MAXIMUM PERMISSIBLE SPEED.	CENTRAL CONTROL GETS POSITION INDICATION OF SWITCHES ON CONTROL BOARD BY LUMINOUS INDICATORS IN THE TRACK DIAGRAM.	SWITCH BLADES, SWITCH MOTOR, AND SWITCH GEAR ARE PERMANENTLY PROVED BY DETECTOR CONTACTS WHEN SWITCH BLADES ARE OUT OF POSITION BY 3/16 INCHES.
NEW YORK CITY TRANSIT AUTHORITY (NYCTA) SECOND AVENUE LINE UNDER CONSTRUCTION	28	YES	WAYSIDE HOME SIGNAL ASPECT INDICATES SWITCH POSITION, TOWER HAS LIGHT INDICATION ON CONTROL PANEL.	FAIL SAFE CIRCUITRY, SWITCH POINTS AND LOCKING CONTINUOUSLY CHECKED, DAILY VISUAL INSPECTION.
PORT AUTHORITY TRANSIT CORPORATION (PATCO)	39	YES	OPERATOR HAS WAYSIDE LIGHT SIGNAL OF SWITCH CONDITION. TOWER HAS LIGHT INDICATION ON BOARD.	TESTED EVERY 30 DAYS WITH 1/4" OBSTRUCTION. CONSTANT FLASHING ON TOWER BOARD PLUS RED SIGNAL AT TOWER.
SISTEMA DE TRANSPORTE COLECTIVO (STC) MEXICO CITY LINE #1, #2, AND #3	21	YES	SEMAPHORE INDICATOR LIGHTS AT SWITCH AND AT CENTRAL CONTROL BOARD.	FAULTY SWITCHES ARE INDICATED BY PERMANENT RED LIGHT IN SEMAPHORE AND/OR ALARMS IN CENTRAL CONTROL.
WASHINGTON METROPOLITAN AREA TRANSIT AUTHORITY (WMATA) UNDER CONSTRUCTION		IDENTIFICATION, LOCAL CONTROL, SWITCH STATUS CONFIRMATION.	POSITION INDICATOR LIGHTS AND STATUS AT CENTRAL CONTROL.	FAIL-SAFE DESIGN; PREVENTIVE MAINTENANCE.

TABLE A-1 SUMMARY CHARACTERISTICS OF EXISTING AND PROPOSED RAIL RAPID TRANSIT SYSTEMS (Sheet 10 of 14)

SYSTEMS

SYSTEM CHARACTERISTICS / MOST AUTOMATED LINE OF TRANSIT AUTHORITY	TRAIN DATA			TRAIN SEPARATION ASSURANCE TECHNIQUE
	IDENTIFICATION AVAILABILITY	DETECTION AVAILABILITY	VELOCITY AVAILABILITY	
BAY AREA RAPID TRANSIT DISTRICT (BARTD) ALL LINES PARTIALLY OPERATIONAL	IDENTIFICATION SYSTEM USES WAYSIDE TRANSMITTER/RECEIVER FOR 36 BIT FSK CODE. IDENTIFICATION AVAILABLE AT TERMINAL ZONES, STATION AND CENTRAL CONTROL.	TRAIN DETECTION AVAILABLE AT STATION AND CENTRAL CONTROL.	ACTUAL SPEED AVAILABLE TO TRAIN OPERATOR.	FIXED BLOCKS CHANGE SPEED CODES AS A TRAIN PASSES INSURING A SAFE STOPPING DISTANCE BETWEEN TRAINS.
CHICAGO TRANSIT AUTHORITY (CTA) LAKE - DAN RYAN LINE		TRACK CIRCUITS (CENTRAL CONTROL).	ALLOWABLE SPEED AND ACTUAL VELOCITY AVAILABLE TO TRAIN OPERATOR.	CONVENTIONAL BLOCK CONTROL
MASSACHUSETTS BAY TRANSPORTATION AUTHORITY (MBTA) RED LINE PARTIALLY OPERATIONAL	AUTOMATIC CAR IDENTIFICATION AT CENTRAL CONTROL.	TRACK CIRCUITS (CENTRAL CONTROL).	ALLOWABLE SPEED AND ACTUAL VELOCITY AVAILABLE TO TRAIN OPERATOR.	FAIL-SAFE DESIGN OF CONVENTIONAL BLOCK CONTROL.
MUNICH METRO WEST GERMANY	IDENTIFICATION OF TRAINS IS ACHIEVED BY INTERMITTENT INDUCTIVE FREQUENCY MULTIPLEX TRANSMITTERS AT TRAINS AND CORRESPONDING RECEIVERS AT TRACKSIDE.	TRACK CIRCUITS (CENTRAL CONTROL).	ALLOWABLE SPEED AND ACTUAL VELOCITY AVAILABLE TO TRAIN OPERATOR.	CONVENTIONAL BLOCK CONTROL. (MOVING BLOCK CONTROL UNDER TEST AT HAMBURG AND HELSINKI).
NEW YORK CITY TRANSIT AUTHORITY (NYCTA) SECOND AVENUE LINE UNDER CONSTRUCTION	IDENTRA SYSTEM, PASSIVE TRAIN COIL CAUSES WAYSIDE EQUIPMENT TO OSCILLATE AT DISCRETE FREQUENCIES.	TRACK CIRCUITS FORMING FIXED BLOCKS, TRAIN LOCATION DISPLAYED ON CONTROL PANEL AND AT COMMAND CENTER.	ALLOWABLE SPEED AND ACTUAL VELOCITY AVAILABLE TO TRAIN OPERATOR.	FIXED BLOCKS CHANGE SPEED CODES ASSURING SAFE STOPPING DISTANCE BETWEEN TRAINS.
PORT AUTHORITY TRANSIT CORPORATION (PATCO)	IDENTRA SYSTEM TRANSMITS FREQUENCY FROM TRAIN TO WAYSIDE RECEIVER.	TRACK CIRCUITS FORMING FIXED BLOCKS. TRAIN LOCATION AVAILABLE TO TOWER.	ALLOWABLE SPEED AND ACTUAL VELOCITY AVAILABLE TO TRAIN OPERATOR.	FIXED BLOCK SYSTEM ALLOWS SAFE STOPPING DISTANCE BETWEEN TRAINS.
SISTEMA DE TRANSPORTE COLECTIVO (STC) MEXICO CITY LINE #1, #2, AND #3	WHEN A TRAIN IS WITHIN A STATION, 20 BITS OF TRAIN IDENTIFICATION CODE, ENTERED BY PUSHBUTTONS, IS SENT TO CENTRAL CONTROL AND DISPLAYED ON THE CONTROL BOARD.	TRACK SHORT CIRCUITING BLOCKS (CENTRAL CONTROL).	ALLOWABLE SPEED AND ACTUAL VELOCITY AVAILABLE TO TRAIN OPERATOR.	CONVENTIONAL BLOCK CONTROL.
WASHINGTON METROPOLITAN AREA TRANSIT AUTHORITY (WMATA) UNDER CONSTRUCTION	AUTOMATIC DIGITAL SYSTEM.	TRACK CIRCUITS (CENTRAL CONTROL).	ALLOWABLE SPEED AND ACTUAL VELOCITY AVAILABLE TO TRAIN OPERATOR.	CONVENTIONAL BLOCK CONTROL.

TABLE A-1 SUMMARY CHARACTERISTICS OF EXISTING AND PROPOSED RAIL RAPID TRANSIT SYSTEMS (Sheet 11 of 14)

SYSTEMS

SYSTEM CHARACTERISTICS / MOST AUTOMATED LINE OF TRANSIT AUTHORITY	OVERSPEED PROTECTION	SPEED PROFILE MODIFICATION	FAILURE/MALFUNCTION	
			DETECTION	CORRECTION
BAY AREA RAPID TRANSIT DISTRICT (BARTD) ALL LINES PARTIALLY OPERATIONAL	WHEEL ROTATIONAL VELOCITY IS CONSTANTLY MONITORED AND COMPARED WITH COMMANDED SPEED. THE RESULTING SIGNAL IS USED TO CONTROL THE MOTORS AND BRAKES.	SIX LEVELS OF SPEED MODIFICATION PERCENTAGE CAN BE IMPOSED UPON THE TRAIN, BY CENTRAL CONTROL, TO AUTOMATICALLY MODIFY THE TRACK CIRCUIT COMMANDED SPEED.	TRACK CIRCUIT FAILURE CAUSES THE TRAIN TO STOP. CENTRAL CONTROL THEN GIVES PERMISSION TO SHIFT TO MANUAL.	CENTRAL CONTACTS A MAINTENANCE CREW FOR FAILURE CORRECTION.
CHICAGO TRANSIT AUTHORITY (CTA) LAKE - DAN RYAN LINE	AUTOMATIC BRAKING PRECEDED BY ACOUSTICAL SIGNAL TO TRAIN OPERATOR.	AUDIO COMMANDS; WAYSIDE MODIFICATION.	LARGELY MOTORMAN DETECTION.	DEPENDS ON TYPE OF MALFUNCTION.
MASSACHUSETTS BAY TRANSPORTATION AUTHORITY (MBTA) RED LINE PARTIALLY OPERATIONAL	ON-BOARD COMPARISON OF ALLOWABLE AND ACTUAL SPEEDS; ACOUSTICAL SIGNAL PRECEDES AUTOMATIC BRAKING.	WAYSIDE ADJUSTMENT.	FAIL-SAFE DESIGN AND VISIBLE INSPECTION.	MAINTENANCE PROGRAM.
MUNICH METRO WEST GERMANY	ON-BOARD COMPARISON OF ALLOWABLE AND ACTUAL SPEED; ACOUSTICAL SIGNAL PRECEDES AUTOMATIC BRAKING.	MANUAL SETTING OF REDUCED BRAKE VOLUME DUE TO SNOW/ICE AND/OR WET/SLIPPERY TRACK CONDITIONS ON OPEN SURFACE LINES.	BY FAIL-SAFE FUNCTION FOR ALL VITAL CIRCUIT ACHIEVED EITHER BY FAIL-SAFE LOGIC OR REDUNDANCY EFFECTING AUTOMATIC APPLICATION OF BRAKES.	
NEW YORK CITY TRANSIT AUTHORITY (NYCTA) SECOND AVENUE LINE UNDER CONSTRUCTION	ON-BOARD COMPARISON OF ALLOWABLE AND ACTUAL SPEED, AUTOMATIC BRAKING, PRECEDED BY ACOUSTIC SIGNAL.	WAYSIDE ADJUSTMENT.	FAIL SAFE DESIGN OF VITAL COMPONENTS CAUSES TRAIN TO STOP.	COMMAND CENTER RADIOS PERMISSION FOR MANUAL OPERATION AND CONTACTS MAINTENANCE FOR FAILURE CORRECTION.
PORT AUTHORITY TRANSIT CORPORATION (PATCO)	SPEED SENSOR ON GEAR BOX FEEDS BACK TO MOTOR CONTROL. 3 MPH OVER COMMANDED SPEED CAUSES BRAKING UNTIL IT IS 3 MPH BELOW COMMANDED.	TRAIN OPERATOR IS VERBALLY INSTRUCTED AS TO SPEED MODIFICATIONS AND HE MANUALLY CONTROLS REDUCED SPEED.	FAIL-SAFE DESIGN OF VITAL COMPONENTS CAUSES TRAIN TO STOP.	MOST NON-CRITICAL FAILURES CAN BE OVERRIDEN BY OPERATOR.
SISTEMA DE TRANSPORTE COLECTIVO (STC) MEXICO CITY LINE #1, #2, AND #3	ON-BOARD COMPARISON OF ALLOWABLE AND ACTUAL SPEEDS. ERROR OF .6 MPH FOR 3 TIRE ROTATIONS CAUSES AUTOMATIC BRAKING.	SPEED IS NOT MODIFIED.	DETECTED BY MEANS OF AN ALARM LAMP IN THE OPERATOR'S CABIN.	THE TYPE OF CORRECTION DEPENDS UPON THE TYPE OF MALFUNCTION.
WASHINGTON METROPOLITAN AREA TRANSIT AUTHORITY (WMATA) UNDER CONSTRUCTION				

TABLE A-1 SUMMARY CHARACTERISTICS OF EXISTING AND PROPOSED RAIL RAPID TRANSIT SYSTEMS (Sheet 12 of 14)

SYSTEMS

SYSTEM CHARACTERISTICS MOST AUTOMATED LINE OF TRANSIT AUTHORITY	DOOR CONTROL		CONTROL SYSTEM REQUIREMENTS FOR HIGHER SPEED AND CLOSER HEADWAYS
	OPERATIONAL	EMERGENCY	
BAY AREA RAPID TRANSIT DISTRICT (BARTD) ALL LINES PARTIALLY OPERATIONAL	STOPPING, DOOR OPENING AND CLOSING AT STATION PLATFORM ARE AUTOMATIC UNLESS CENTRAL CONTROL OR OPERATOR HOLD DOORS OPEN.	MANUAL DOOR LEVERS ALLOW DOOR OPENING WHEN TRAIN MOTION IS LESS THAN 2 MPH.	FULL SYSTEM NOT OPERATIONAL AT PRESENT.
CHICAGO TRANSIT AUTHORITY (CTA) LAKE - DAN RYAN LINE	VEHICLE STOPS, CONDUCTOR OPENS DOOR (REMOVING POWER).	CONDUCTOR CAN OPEN DOORS AT ANY TIME WHICH REMOVES POWER VIA POWER CONTROL RELAY.	UTILIZE EXTENSIVE CAB SIGNALLING; REMOVE OLDER CARS.
MASSACHUSETTS BAY TRANSPORTATION AUTHORITY (MBTA) RED LINE PARTIALLY OPERATIONAL	UPON TRAIN STOP, MANUAL OPERATION BY CONDUCTOR.	EXTENSIVE EMERGENCY PROCEDURES IN MBTA RULE BOOK.	FULLY AUTOMATIC OPERATIONS BASED ON FAIL-SAFE DESIGN.
MUNICH METRO WEST GERMANY		EMERGENCY DOOR OPENING SWITCHES OR LEVERS BEING PROVIDED.	INTRODUCTION OF MODERN FAIL-SAFE ATC SYSTEM IN CONNECTION WITH ATO.
NEW YORK CITY TRANSIT AUTHORITY (NYCTA) SECOND AVENUE LINE UNDER CONSTRUCTION	TRAIN STOPS; OPERATOR OPENS DOORS; OPERATOR CLOSES DOORS; TRAIN PROCEEDS.	OPERATING PERSONNEL CAN OPEN INDIVIDUAL DOORS USING KEY OR LEVER.	AUTOMATIC TRAIN SUPERVISION, MOVING BLOCK SYSTEMS.
PORT AUTHORITY TRANSIT CORPORATION (PATCO)	TRAIN STOPS; OPERATOR OPENS DOORS; OPERATOR CLOSES DOORS; TRAIN PROCEEDS.	EVACUATE THROUGH END DOOR FROM CAR TO CAR TO WAYSIDE.	ADEQUATE TRAIN STORAGE AREAS. CONTINUOUS SPEED CONTROL BY BLOCKS. HAVE BLOCK LENGTH AND TRAIN SPACING VARY WITH SPEED. PROVIDE MORE INFORMATION TO CONTROL TOWER. ADD REVERSE SIGNALS.
SISTEMA DE TRANSPORTE COLECTIVO (STC) MEXICO CITY LINE #1, #2, AND #3	OPERATOR CONTROLLED. TRAIN STOPS, DOORS ARE OPENED AND CLOSED, TRAIN PROCEEDS.	WHEN A PASSENGER EMERGENCY BRAKE IS OPERATED, THE DOORS AUTOMATICALLY UNLOCK AND THE DOORS CAN BE EASILY OPENED. OPERATOR CAN ALSO UNLOCK DOORS.	REDUCE BLOCK LENGTH, REDUCE TRAIN DWELL TIME IN STATIONS AND INSTALL ATO TO TRAINS.
WASHINGTON METROPOLITAN AREA TRANSIT AUTHORITY (WMATA) UNDER CONSTRUCTION			

TABLE A-1 SUMMARY CHARACTERISTICS OF EXISTING AND PROPOSED RAIL RAPID TRANSIT SYSTEMS (Sheet 13 of 14)

COMMUNICATIONS

SYSTEM CHARACTERISTICS / MOST AUTOMATED LINE OF TRANSIT AUTHORITY	WAYSIDE-TO-VEHICLE	STATION-TO-VEHICLE	CENTRAL-TO-VEHICLE	WAYSIDE-TO-STATION
BAY AREA RAPID TRANSIT DISTRICT (BARTD) ALL LINES PARTIALLY OPERATIONAL	FREQUENCY SHIFT KEYED (FSK) TRACK CIRCUIT SPEED, PERFORMANCE MODE, STOPPING IDENTITY AND DOOR COMMANDS.	TWO WAY RADIO (160 MHZ) VIA CENTRAL SWITCHBOARD (PABX).	TWO WAY RADIO, DIGITAL TRANSMISSION SYSTEM (DTS) VIA STATION CONTROLLER DIGITAL TIME MULTIPLEX (MUX).	TWO WAY MAINTENANCE PHONE VIA CENTRAL PABX, MUX FOR DATA TRANSMISSION.
CHICAGO TRANSIT AUTHORITY (CTA) LAKE - DAN RYAN LINE	NONE	TELEPHONE	TRAIN PHONE	NONE
MASSACHUSETTS BAY TRANSPORTATION AUTHORITY (MBTA) RED LINE PARTIALLY OPERATIONAL	SINGLE CHANNEL TWO FREQUENCY HIGH BAND VOICE, NARROW BAND FM OPERATED HALF DUPLEX WITH MOBILE REPEAT.	SINGLE CHANNEL TWO FREQUENCY HIGH BAND VOICE, NARROW BAND FM OPERATED HALF DUPLEX WITH MOBILE REPEAT.	SINGLE CHANNEL TWO FREQUENCY HIGH BAND VOICE, NARROW BAND FM OPERATED HALF DUPLEX WITH MOBILE REPEAT AND TONE COMMAND.	TWO-WAY PORTABLE RADIO WITH MOBILE REPEAT.
MUNICH METRO WEST GERMANY				
NEW YORK CITY TRANSIT AUTHORITY (NYCTA) SECOND AVENUE LINE UNDER CONSTRUCTION	WALKIE-TALKIE CARRIED BY SUPERVISORY OPERATING PERSONNEL, ON-BOARD TRAIN RADIO.	TWO-WAY RADIO AT KEY DISPATCHER LOCATIONS.	TWO-WAY RADIO.	SYSTEM TELEPHONE
PORT AUTHORITY TRANSIT CORPORATION (PATCO)	THROUGH CENTRAL	THROUGH CENTRAL	TRAIN PHONE	THROUGH CENTRAL
SISTEMA DE TRANSPORTE COLECTIVO (STC) MEXICO CITY LINE #1, #2, AND #3	NO	NO	RADIO CARRIER AND SIGNAL TELEPHONE.	DIRECT WIRE TELEPHONE.
WASHINGTON METROPOLITAN AREA TRANSIT AUTHORITY (WMATA) UNDER CONSTRUCTION	THROUGH ATC/ATO BY TDM TELEGRAM.	BY TRAIN RADIO COMMUNICATION SYSTEMS OVER TELEPHONE.	BY TRAIN RADIO COMMUNICATION SYSTEMS OVER TELEPHONE.	SIGNAL TELEPHONE OVER DIRECT WIRE.

TABLE A-1 SUMMARY CHARACTERISTICS OF EXISTING AND PROPOSED RAIL RAPID TRANSIT SYSTEMS

COMMUNICATIONS

SYSTEM CHARACTERISTICS MOST AUTOMATED LINE OF TRANSIT AUTHORITY	WAYSIDE-TO-CENTRAL	CENTRAL-TO-STATIONS	WAYSIDE-TO-WAYSIDE	STATION-TO-STATION
BAY AREA RAPID TRANSIT DISTRICT (BARTD) ALL LINES PARTIALLY OPERATIONAL	MAINTENANCE PHONE, MUX AND DTS FOR DATA TRANSMISSION.	PABX AND DTS	TWO WAY MAINTENANCE PHONE.	PABX
CHICAGO TRANSIT AUTHORITY (CTA) LAKE - DAN RYAN LINE	NONE	TELEPHONE	NONE	TELEPHONE
MASSACHUSETTS BAY TRANSPORTATION AUTHORITY (MBTA) RED LINE PARTIALLY OPERATIONAL	SINGLE CHANNEL TWO FREQUENCY HIGH BAND VOICE, NARROW BAND FM OPERATED HALF DUPLEX WITHOUT MOBILE REPEAT.	HARD WIRE INTERCOM.	HARD WIRE PRIVATE TELEPHONE.	SINGLE CHANNEL TWO FREQUENCY HIGH BAND VOICE, NARROW BAND FM OPERATED HALF DUPLEX WITH MOBILE REPEAT.
MUNICH METRO WEST GERMANY				
NEW YORK CITY TRANSIT AUTHORITY (NYCTA) SECOND AVENUE LINE UNDER CONSTRUCTION	MAINTENANCE, POLICE AND OPERATING SUPERVISION VIA WALKIE-TALKIE, SYSTEM TELEPHONE.	PUBLIC ADDRESS, TWO-WAY RADIO TO KEY DISPATCHERS, SYSTEM TELEPHONE.	SYSTEM TELEPHONE, MAINTENANCE AND POLICE AND OPERATING SUPERVISION VIA WALKIE-TALKIE.	KEY DISPATCHERS HAVE P.A. FACILITIES, SYSTEM TELEPHONE.
PORT AUTHORITY TRANSIT CORPORATION (PATCO)	TWO-WAY RADIO IN TRUCKS TO CENTRAL TOWER, LINDENWOLD SHOP AND POLICE, MAINTENANCE HEADQUARTERS PLUS WALKIE-TALKIES SAME BAND.	CLOSED CIRCUIT T.V. IN ALL STATIONS. BELL TELEPHONE IN ALL STATIONS.	TWO-WAY RADIO IN TRUCKS TO CENTRAL TOWER, LINDENWOLD SHOP AND POLICE, MAINTENANCE HEADQUARTERS PLUS WALKIE-TALKIES SAME BAND.	THROUGH CENTRAL
SISTEMA DE TRANSPORTE COLECTIVO (STC) MEXICO CITY LINE #1, #2, AND #3	DIRECT WIRE TELEPHONE AND SIGNAL TELEPHONE.	AUTOMATIC TELEPHONE, DIRECT WIRE TELEPHONE, SIGNAL TELEPHONE, TICKET OFFICE TELEPHONE.	NO	AUTOMATIC TELEPHONE
WASHINGTON METROPOLITAN AREA TRANSIT AUTHORITY (WMATA) UNDER CONSTRUCTION	VIA STATION	BY PABX	VIA STATION	BY PABX

APPENDIX B

SURVEILLANCE AND COMMUNICATIONS FOR RAIL RAPID TRANSIT SYSTEMS

B1. THE GENERAL SYSTEM

An automatic train control system requires data for vehicle regulation (spacing, merging, diverting, etc.) and for system management. This Appendix is primarily concerned with vehicle regulation involving train and track surveillance and delivery of commands for control of vehicles and track network. The requirement for transmission of these data for presently planned systems can be met by present technology but the reliability and safety trade-offs have not been subject to extensive analysis particularly in the operating environment of a rail rapid transit system.

A general communication system configuration is shown in Figure B-1. It consists of

1. Train-mounted equipment
2. Track-mounted equipment
3. Wayside-mounted equipment
4. Station control equipment
5. Central control equipment

In general, the vehicle receives commands and information on position, velocity, braking, switching, routing, and door opening and closing. The vehicle may transmit information on position, velocity, identification, command acknowledgement, operating status of components and emergency data.

The track-mounted equipment may be used to provide vehicle position information by use of sensors or transmitters mounted along the track or the track itself may be used to carry signal currents for wayside-vehicle communication. In order of the density of installations, there are the following elements:

a. Central control
b. Station control
c. Wayside station
d. Block section

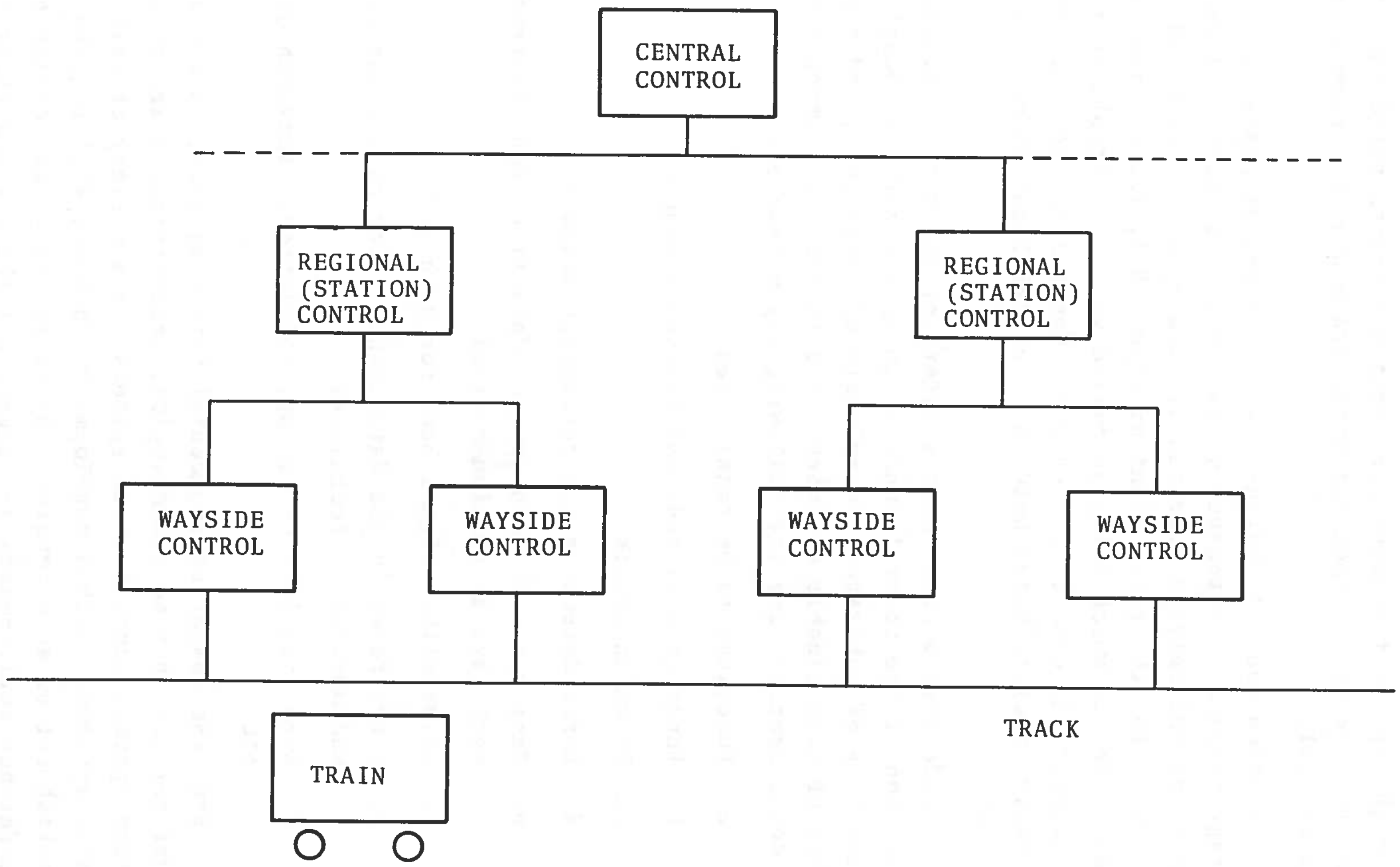


Figure B-1 Generalized Command/Control System Configuration

Although wayside functions are sometimes incorporated into control stations, the most common automatic train control systems use wayside control.

Station control systems may be located at passenger stations, storage yards or maintenance yards. Regional control of routing, scheduling and related operational strategies is exercised at these stations. For the arrangement of Figure B-1, the station is the lowest level at which fully automatic vehicle control, routing and dispatching can be carried out. Control may be concentrated centrally or distributed between a central location and the stations.

Trade-offs bearing on the safety of the system involve the allocation of the control function among the various locations, reliability of subsystems, complexity of subsystems, and the total number of maintainable components and subsystems. Among the trade-off considerations are the following key parameters.

a. Functions to be transmitted

b. Function amplitude and frequency ranges

c. Function precision

d. Error detection and correction methods

e. Data rates in each type of data link (vehicle-track network-wayside station-central)

f. Noise within signal band for each link

g. Error rates in the data channels for particular coding and modulation techniques

h. Specifications of coding, modulation, bandwidth delays, etc.

From the meager environmental data available, it appears almost certain that no technological break-throughs are required to develop optimal communication systems for a variety of rail rapid transit systems. Such a development, however, will require the establishment of an extensive body of knowledge concerning electrical interference environments and signal reliability and their dependence on propulsion and power generation techniques. Such information is presently unavailable except for particular limited subject areas where it has been obtained from current railroad technology.

The vehicle-to-wayside link seems to be the most limited in terms of the presently experienced high noise and data error rates. The communication system for a rail rapid transit automatic train control system requires continuous data rates of several thousand baud. Existing railroads use rates which are an order of magnitude lower. The higher rate requirements for a rail rapid transit system is due to higher traffic loads and to the need to transmit greater amounts of system status information for safety enhancement.

B2. SIGNALING FUNDAMENTALS

If only one train occupies a section of track, there is no need for signaling or control. In the case of two or more trains, collision prevention procedures are necessary. In general, two way traffic requires steps to prevent rear end and head on collisions. Junctions and intersections must be protected from conflicting movement.

The original method of handling traffic on one way lines was by timed interval dispatching. Variation of train speeds led to the division of the line into segments, or blocks, each controlled by an individual equipped with a signaling device who only allowed one train in the block at a time. The same control requirement applied to single lines carrying two-way traffic. Historically, enforcement on such lines was carried out by requiring the driver to be in physical possession of a token before entering a block. He relinquished it on leaving and it could then be used by a driver of a train going in the opposite direction. The modern equivalent of this procedure allows a train to enter a single-line section on a clear signal only; however, the starting signals are electrically interlocked to avoid opposing movement.

The two vitally important operations that must be performed in all surveillance systems are

1. Check that train is complete on exit from block which is then declared clear.
2. Provide for the effect of a train overrunning a block by provision of an overlap or its equivalent.

The latter requirement may be ignored in a rapid rail system since the train and block lengths are relatively short.

Historically, control commands to the train in the form of wayside mechanical and/or optical signals were actuated mechanically or electrically. Interlocking (equivalent of token exchange) was effected either by mechanical linkage or electrical relay. At the present time cab signals received on the train from the wayside provide information to the driver. They either repeat lineside signals or provide the only train signals in the absence of lineside signals. Automatic train protection can be established through the cab signals, i.e., automatic action on the power and braking system of the train occurs in the event a signal is disobeyed, or speeds are controlled when too high to conform with the stopping distance for the fixed block arrangement. This is the fail-safe principle, always used in these systems. It is defined as a characteristic of a system which ensures that any malfunction affecting safety will cause the system to revert to a state that is generally known to be safe. Additionally it must be impossible to set up conditions permitting conflicting moves. This applies to design as well as manufacture. It pertains to mechanical, electrical and electronic apparatus alike. This is the traditional form of the principle and the absolute quality assumed is illusory.

B3. TRADITIONAL SIGNAL CIRCUITRY

Two categories of signal circuits may be defined: vital (safety) circuits used for train control and interlocking; non-vital circuits used for supervision and indication. Safety circuits are always designed on the closed-circuit principle as illustrated in the simple track circuit of Figure B-2. In this example, an electric current energizes the track circuit relay (its normal state). This allows a mechanical function to be unlocked, a route set and a signal cleared to permit the passage of a train. When a train enters this section of track the current is shunted through the wheels and axle thus de-energizing the relay. The de-energized relay activates the appropriate controls to produce a track-occupied signal. A short circuit or the failure of any component (rail, bond, lead, power supply) will have the same effect as train occupation and will place control and signaling in a restrictive or prohibitive mode.

This model of the closed circuit fail-safe design is used in the design of more elaborate systems employing coded track circuits in an attempt to preserve the fail-safe nature of the simple track circuit. Since failure of any component results in a track-occupied signal, high equipment reliability is required in order to ensure continuous system operation. This is accomplished by exercising great care in specification of components and circuit design and by the provision of duplicate power supplies and feeders, supported by standby facilities, which are automatically activated on failure of the original equipment.

An alternate to adapting the fail-safe principle of the simple track circuit to elaborate systems is the adoption of safety principles based on system considerations which could lead to establishment of hierarchical safety levels and more general methods of applying safety principles to system design.

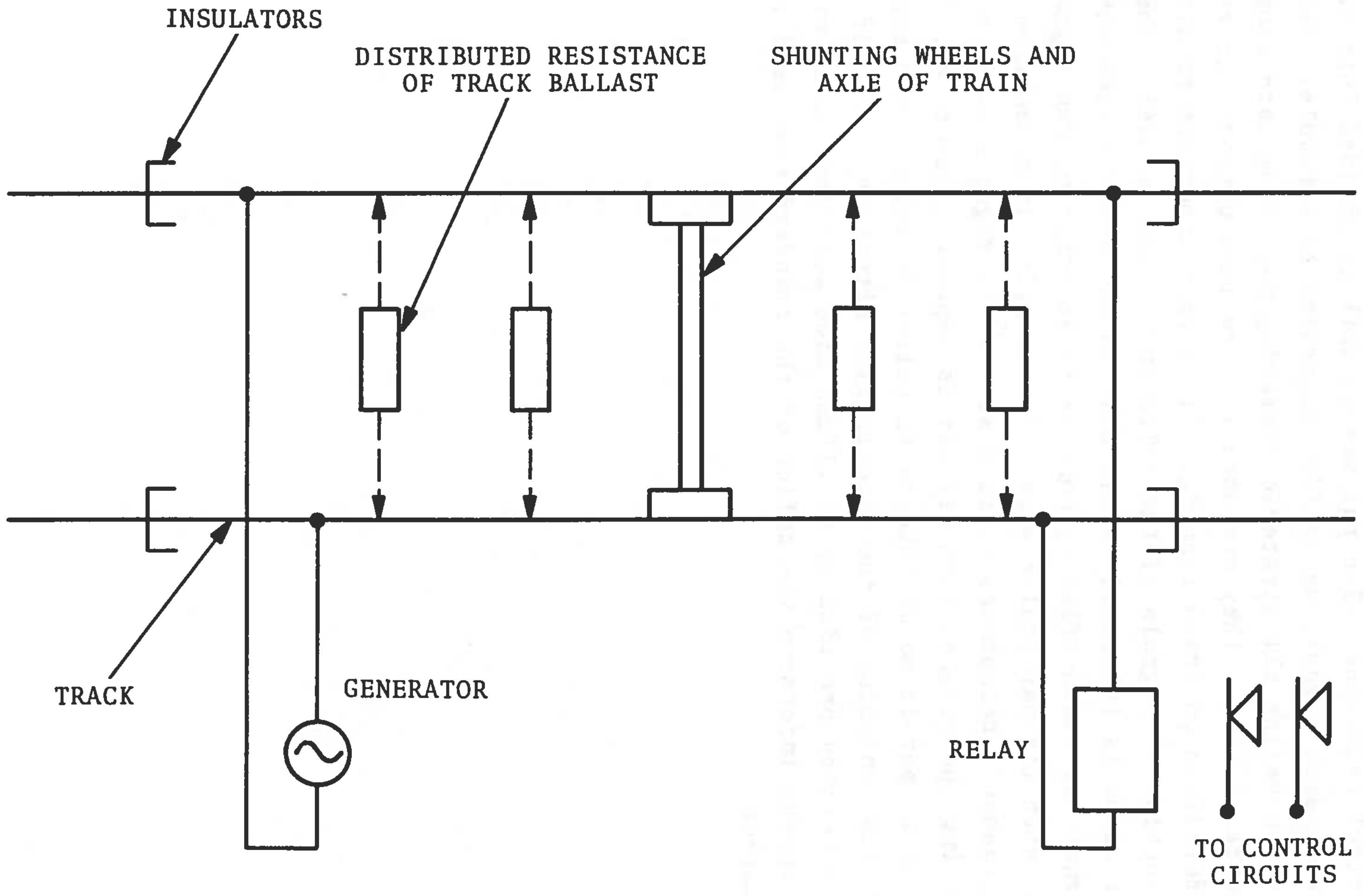


Figure B-2 Insulated Track Circuit

One of the most important circuits in train operation is the control telephone. The railway network is divided into control areas, each organizing traffic according to schedule. Telephone links covering all strategic operating points emanate from a central office. They are used to give instructions and receive information on train running. It is very important to avoid misdirection of signals if the telephone system is used. This misdirection is inherently avoided in an automated system where signals are identified by code or by associating the signal meaning with its particular wire. For example, in connection with enginemen's telephones located at certain signals used in interlocking operations, each circuit is separate, secure and identified so as to permit no mistake as to caller location, thus avoiding the obvious confusion of the interlocking situation. Identification is sometimes provided by an illuminated describer board at the telephone informing the caller of the standard name used for that location.

B4. METHODS FOR MEASURING POSITION OF VEHICLES

There are two basic ways of obtaining position information on a vehicle. The position of the vehicle may be determined by

1. A wayside measurement, carried out by receiving, at wayside, the signal of an on-board vehicle signaling device or by measuring, at wayside, the perturbation of the environment caused by the presence of the vehicle.
2. An on-board measurement of position by monitoring of fixed wayside signals.

Examples of techniques which may be used for vehicle surveillance are discussed in the following paragraphs. The discussion is qualitative and a more detailed study of track circuits and inductive systems is presented later.

Vehicle Surveillance Methods

A. Block Sections - The track circuit shown in Figure B-3 uses one continuous rail and divides the other into insulated block sections. The continuous rail serves to conduct the vehicle propulsion current back to the power generating equipment. Each block has a generator and a receiver. The signal at the receiver is attenuated when a shunting axle and wheels contact the rail. If the receiver signal drops below a preset level the speed command transmitter in the preceding block is switched to zero velocity. The speed command transmitter signal is received by the vehicle and is used to bring the vehicle to the commanded speed.

When a train enters a block, a pulse is transmitted to each of several preceding blocks, activating switching relays to establish a profile of speed signals in those blocks. The most important source of interference is the propulsion current carried by the same conductor, which makes it difficult to detect the occupancy signal current. The shunt resistance of the conducting

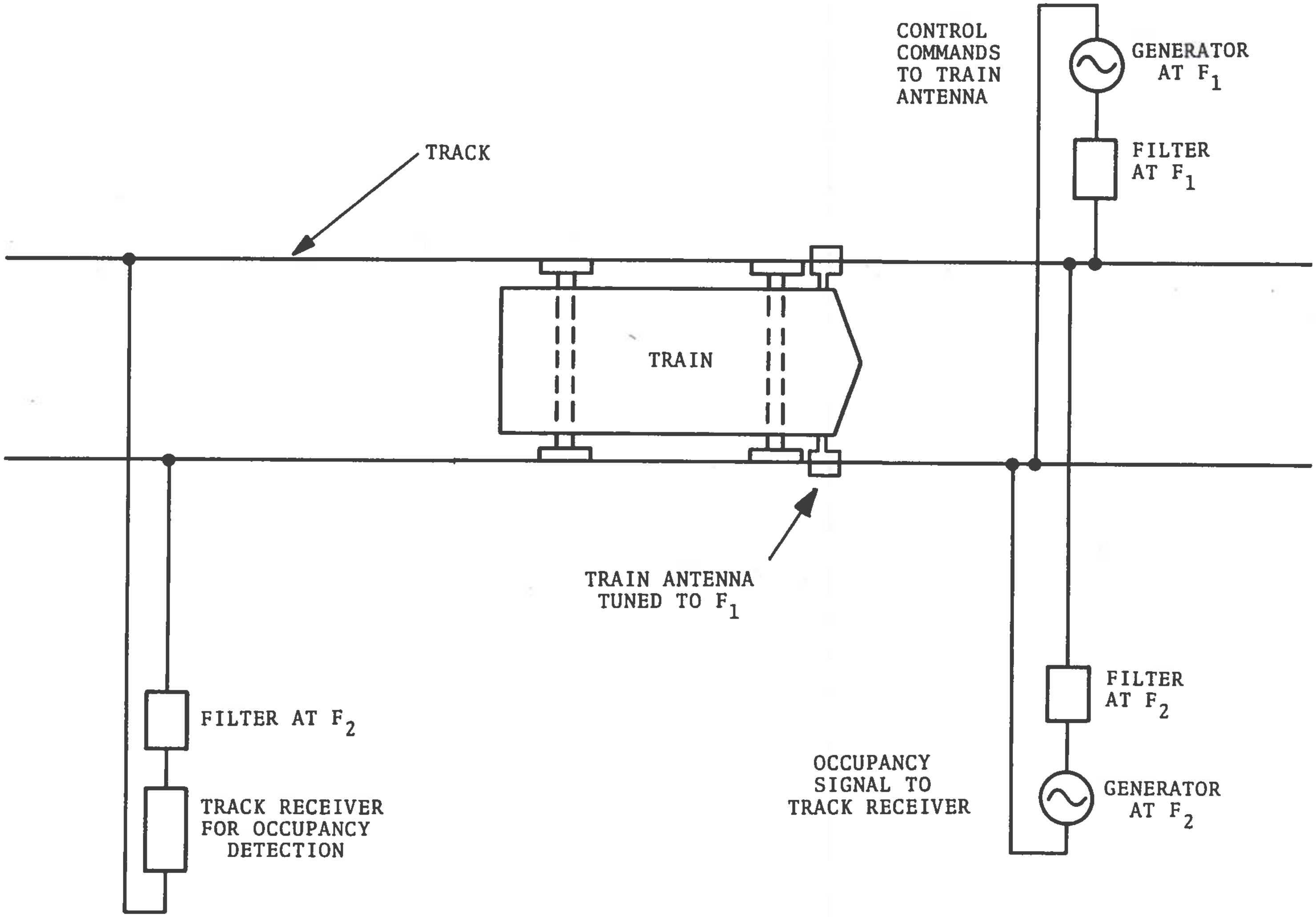


Figure B-3 Track Circuit

earth, (ballast), between rails serves to attenuate the occupancy signal and severely limits the allowable maximum track-wheel contact resistance. The self inductance of the track limits upper signal frequencies to 10 kHz. The range of signals varies from DC, (to operate relays), to audio frequency carriers, frequency modulated by error connecting coded signals. This system is able to detect a vehicle which is without any source of communication. A separate communication system is required to connect to the stations.

B. Inductive Impedance - In this system, shown in Figure B-4, insulated wire loops are installed between the rails. An impedance bridge is used to measure the impedance of the loop; the value being dependent on whether or not a train occupies the track above the loop. This effect depends on the volume of metal in proximity to the loop. Since wheel-rail contact dependence is eliminated, the system is less dependent on the railroad environment. Car size loops of 100 feet, employing frequencies up to 200 kHz allow operation in a spectral region relatively uncluttered by trackside and propulsion current noise. Interrogation of the detectors can be carried out by electronic or mechanical switches. Speed control signals can be inductively coupled to the vehicle via the occupancy detection loop. A separate communication system to the station is required.

C. Signal Blocking - In this system, shown in Figure B-5, a signal source is located parallel to the track. The receiver is located on the opposite side of the track. The normally received signal is attenuated by the vehicle. The transmitter and receiver may be long, distributed elements or they may consist of several discrete elements with a logic requirement for several pairs to be attenuated. The frequencies employed may range from 1MHz to optical.

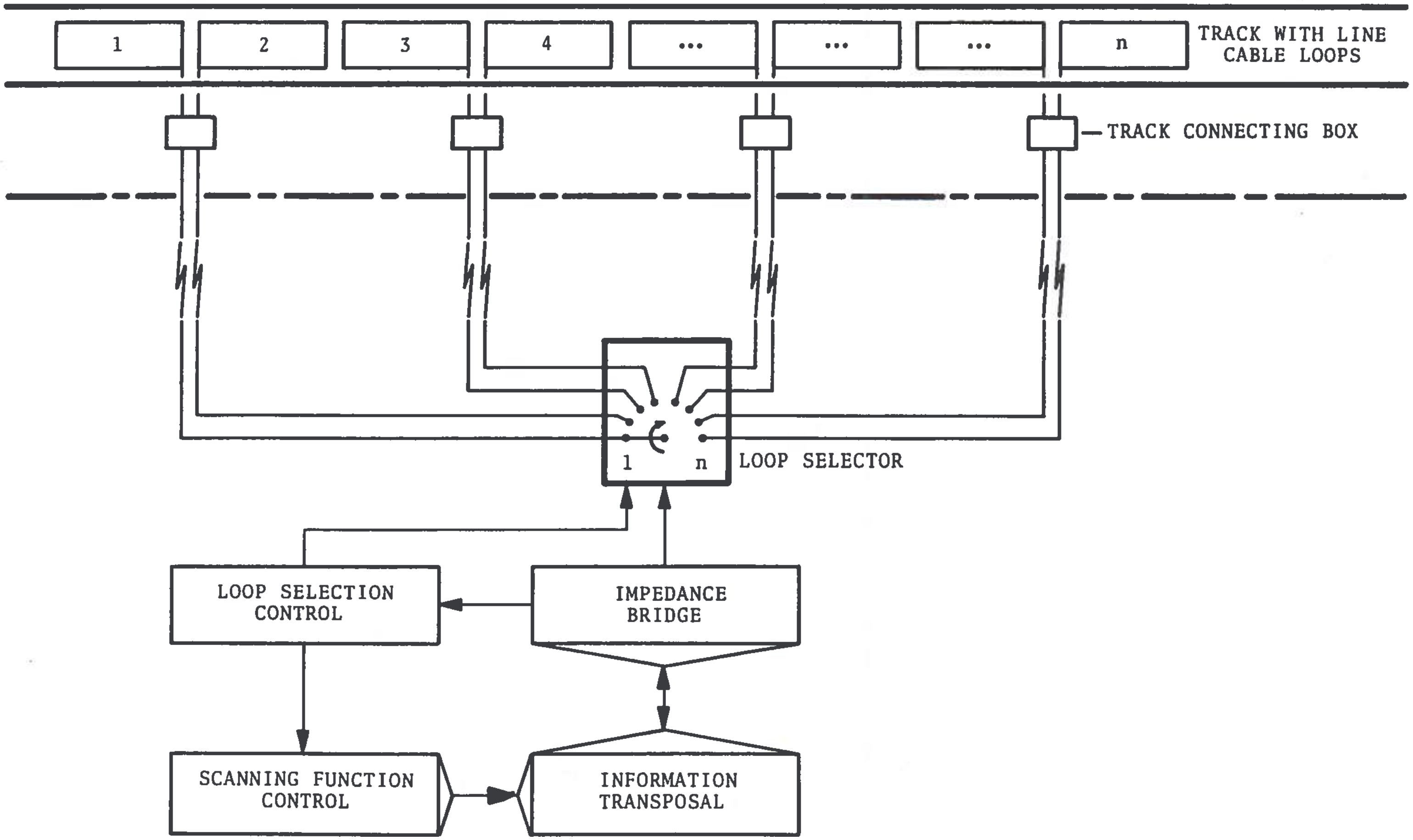


Figure B-4 Occupancy Detection by Impedance Measurement

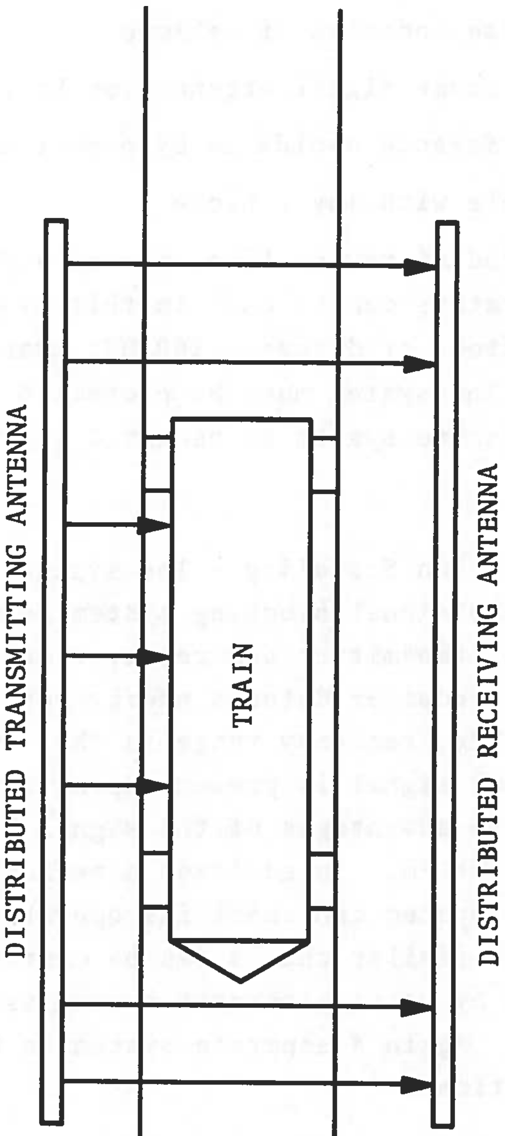


Figure B-5 Occupancy Detection by Signal Blocking

The advantages of the scheme are

a. Precise location of vehicle

b. Very large signal attenuation by the vehicle

c. Interference avoidance by proper choice of frequency

d. Useable with any vehicle

Distributed microwave line sources and detectors with semiconductor generators can be used in this system. Discrete signal lamps and detectors or discrete 200 MHz transmitter-receivers can also be used. The system must be protected against vandalism and weather. A separate system is required to communicate with the station.

D. Reflection Signaling - The system, shown in Figure B-6, is similar to the signal blocking system shown in Figure B-5 but differs in that transmitter and receiver are on the same side of the track. The receiver detects energy reflected from the vehicle as it passes. The frequency range is the same as that of the system in Figure B-5 but signal is present upon train occupancy rather than absent. The advantages of the signal blocking system also accrue to this system. In addition a reflector periodically inserted into the system can check its operation. It should be pointed out that similar checks can be carried out with the signal blocking system by using alternate transmission paths but it is more difficult. Again a separate system is required for communication with stations.

E. Wayside Detects Vehicle Identification - In this system, shown in Figure B-7, the train carries a transmitter which sends out an identity-coded signal. This is received by receivers along the wayside. The received signal, coded with wayside position identification, is sent to the wayside box for processing. An additional system is required for communicating with the stations. The system can be inverted so that the train receives digital messages from transmitters along the wayside thus identifying the

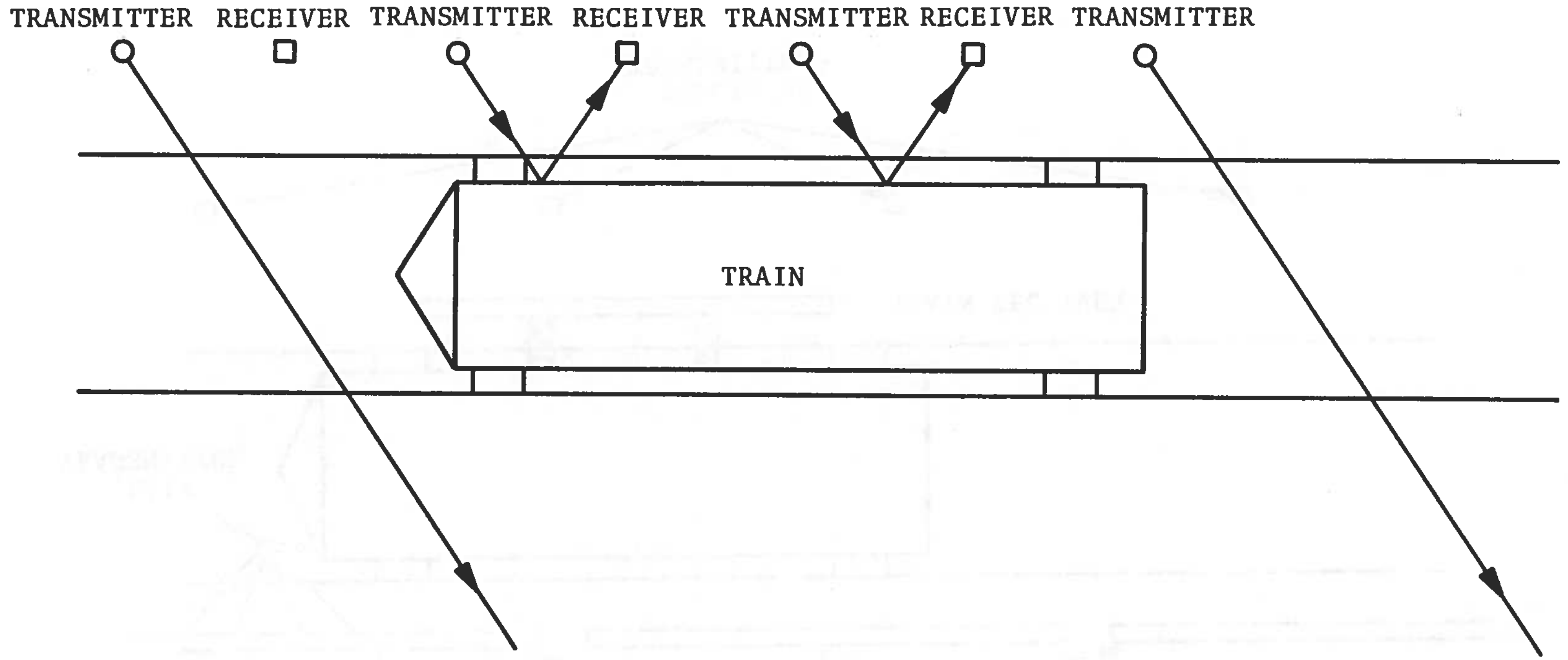
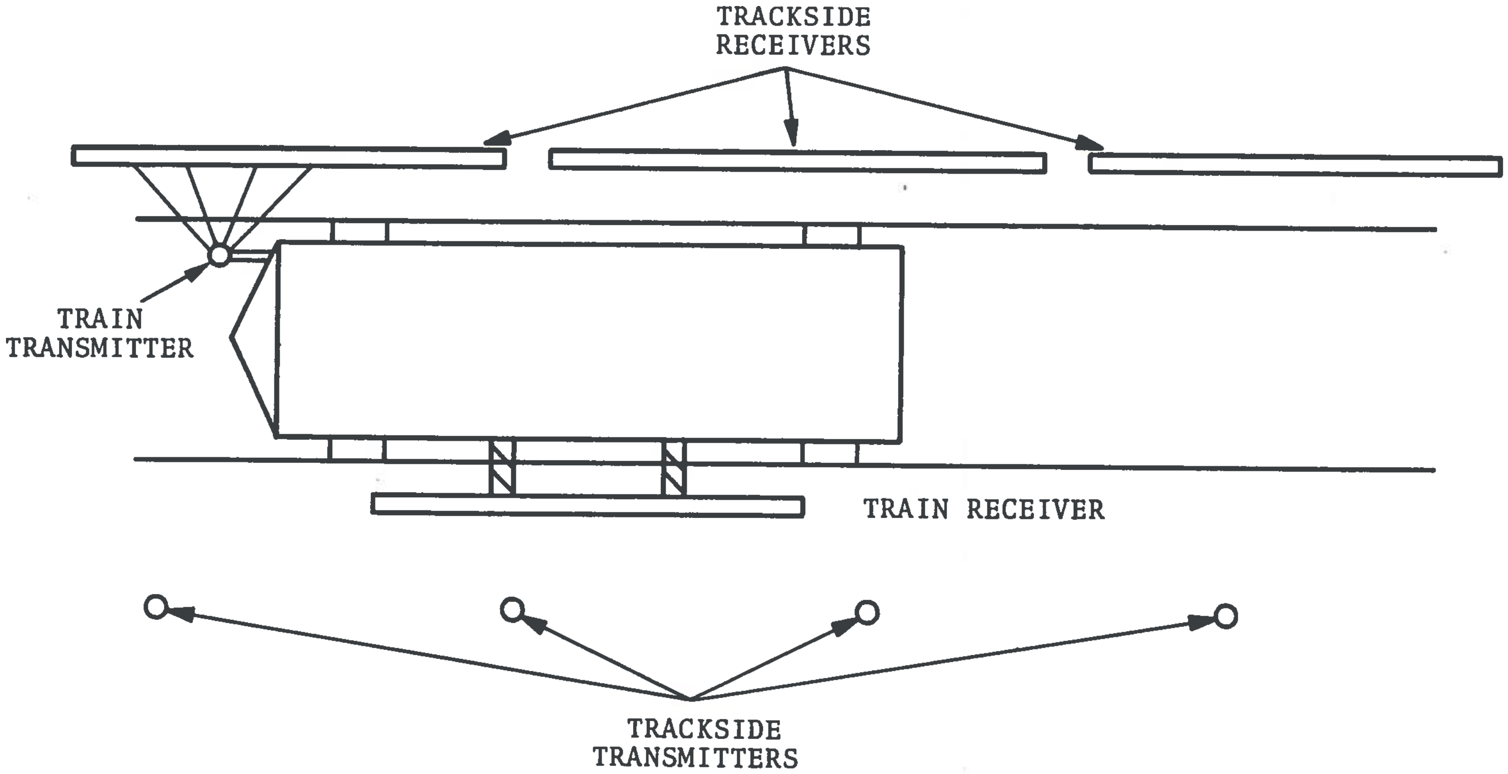


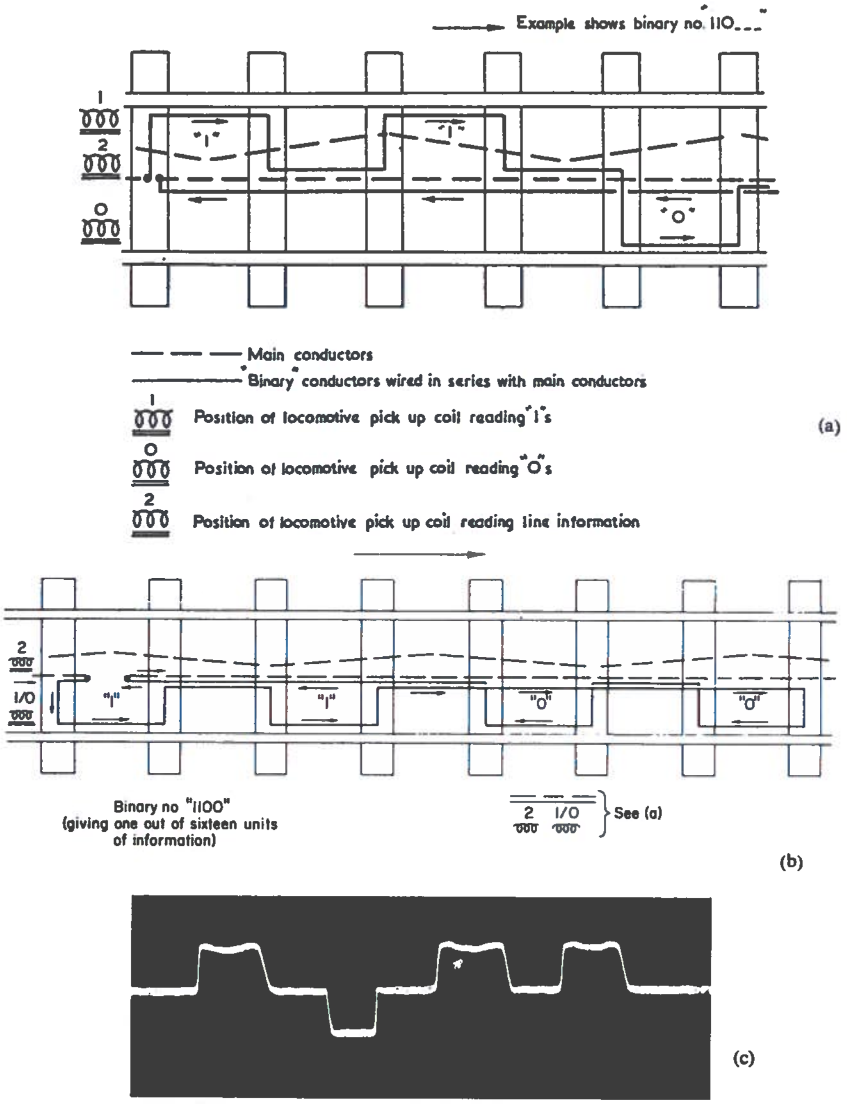
Figure B-6 Occupancy Detection by Signal Reflection



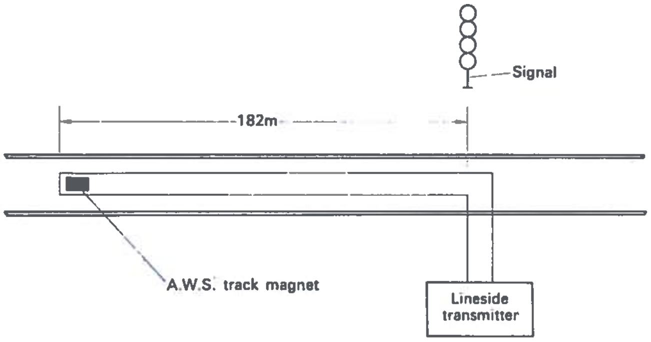
NOTE: Train sends identification to Wayside or, in alternate system, Wayside sends location signal to Train.

Figure B-7 Wayside Detection of Vehicle Identification position. The wayside, station or central receives the train acknowledgement from a train transmitter. The requirement for a functioning transmitter aboard the train need not detract from the overall safety of the system. Stand-by self-contained power supplies can be designed for the required degree of safety. A feed-back message from the wayside confirming the identification can be incorporated into the system. Similar feed-back confirmation of a wayside generated speed command can be effected. Either an inductive system or a radiating system can be used here, so that the possible frequency range is from 10 kHz to optical. The ability to operate removed from the spectral region of greatest interference is a significant advantage.

F. Combined Surveillance-Communication System - An alternative to the track circuit is shown in Figure B-8. This has had considerable development by British Railways and the Deutsche Bundesbahn and consists of configurations of insulated wire laid along the roadbed to carry signals in the frequency range 20-150 kHz. The vehicle can, by inductive coupling, transmit to or receive from this wire. In addition to allowing conventional modulated carrier messages to be exchanged between line and train, the spacing of the wires can be varied along the line thus modifying the signal and providing information to the train about the fixed track situation and to communicate to the line the train position. If one of the conductors is arranged in a triangular configuration, an approximately sinusoidal wave is received by an inductive loop aboard the train. (See Figure B-9). If the wave length of the conductor, i.e., the physical length of the repetitive pattern, is chosen as 8.8 ft. the modulation frequency received aboard the train would be 10 Hz for a train traveling at 60 mph. Shortening the physical length of the repetitive pattern can be used to signal speed restriction for curvature of track or other local requirements. In addition, loops can be introduced to provide binary information. Figure B-10 illustrates this. A scheme is shown for a complete system and an experimental system

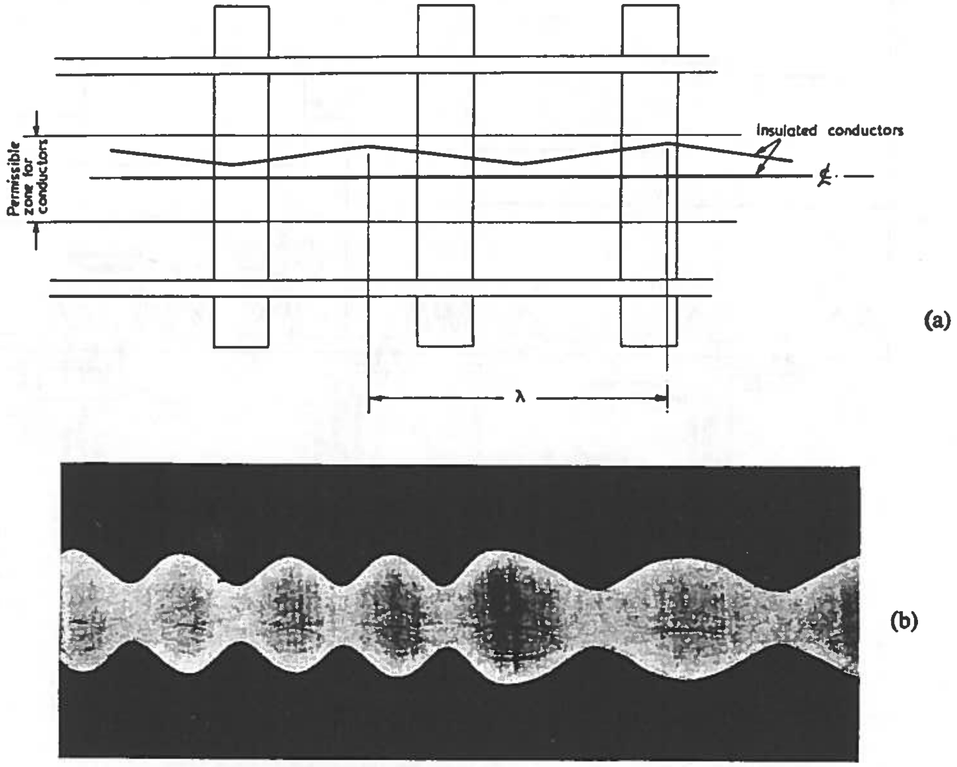


(a) Method of writing binary no. in to track. (b) Binary no. produced by phase comparison. (c) Oscillogram of binary no. derived from track conductors. Binary information from track conductors.



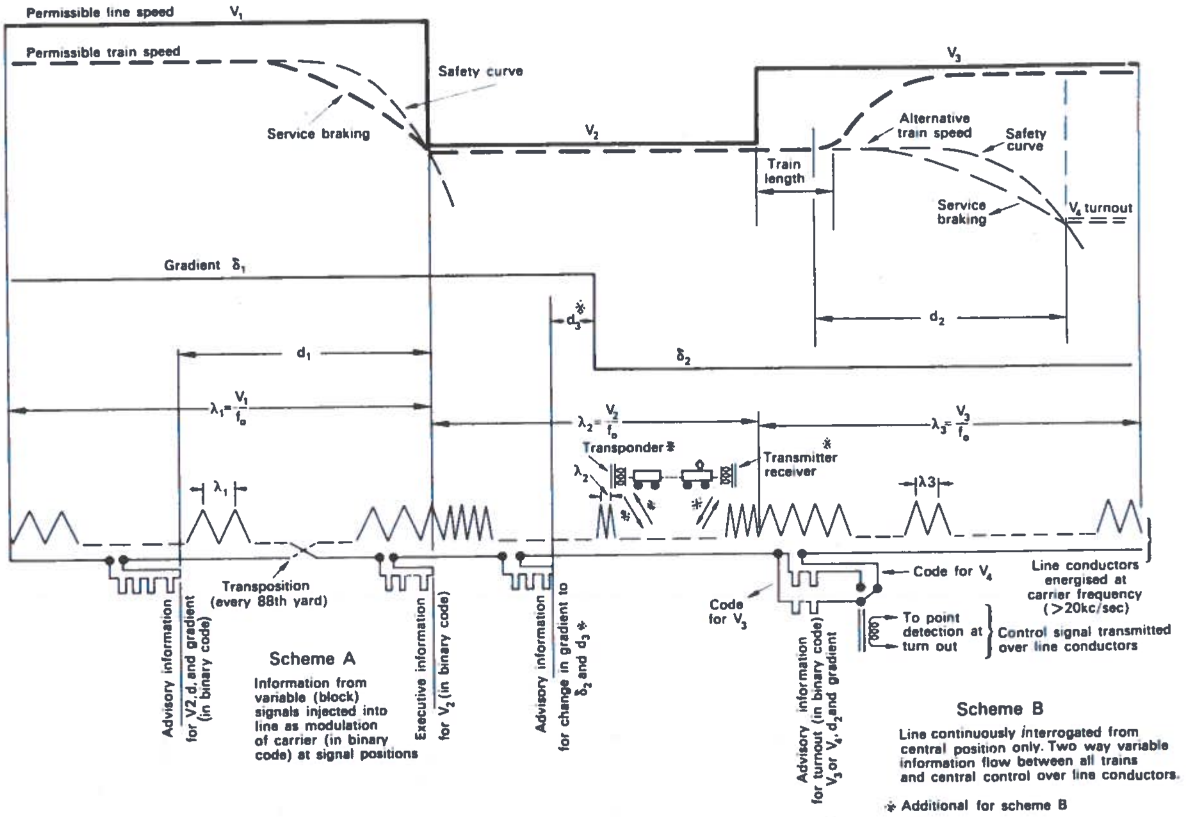
Combination of inductive loops and track magnets.

Figure B-8 Combined Surveillence/Communications System

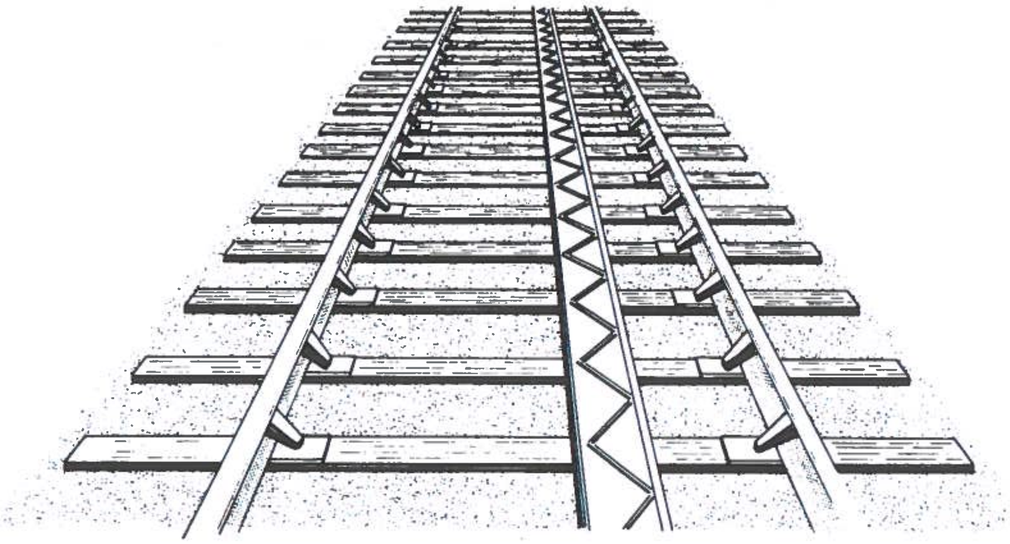


(a) Conductor arrangement used to indicate line speed.
(b) Example of signal produced by motion of train.
Speed measurement from line conductors.

Figure B-9 Signal Modulation Induced by Train Motion over Track Conductors



Basic communication system for continuous-speed control.



Experimental installation of line conductors.

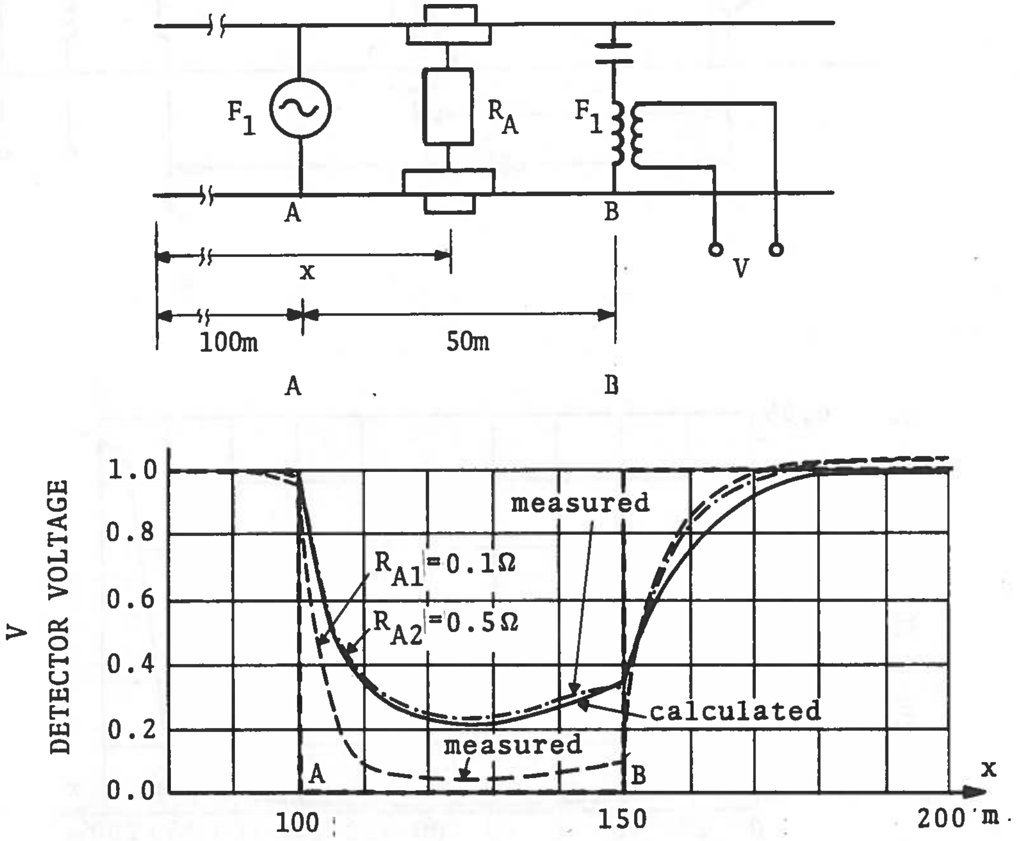
Figure B-10 Communications for Continuous Speed Control on British Rail at West Drayton. Figure B-8 shows a technique employing redundant systems, (inductive loops and track magnets), to attain fail-safe operation. The loop transmits a wayside generated signal. The field of the track magnet is detected by the same pickup coil that senses the wayside signal and thus the train is alerted for a wayside message. Without the track magnet trigger, a failure of the loop circuit would remain undetected.

B5. TRACK CIRCUITS

Track circuits may be divided into two types: continuous track circuits and insulated track circuits. The names refer to circuits used with continuous conducting rails and circuits used with rails which are divided into block lengths and insulated from each other. At high frequencies, long blocks of each kind present much the same problem so only continuous track circuits will be discussed. Later in this Appendix the essential differences in application of short blocks will be briefly described.

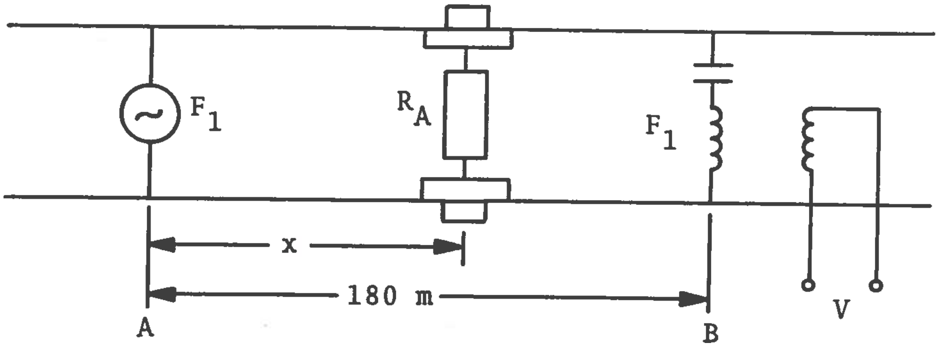
The operation of the basic continuous-track signal circuit (See Figure B-11) is as follows. The generator at A is attached to the running rails. At some distance along the rails, at B, a detector is attached to the running rails. The section of track AB is called a block. When an axle-wheel set enters the block, some of the current which would flow to the detector in the unoccupied state is shunted through the axle and flows back to the generator. The decrease in current through the detector is interpreted as an occupancy signal for the block AB. An alarm is activated when the signal falls below some threshold value. The factors involved in track circuit design (ignoring interference for the moment) are

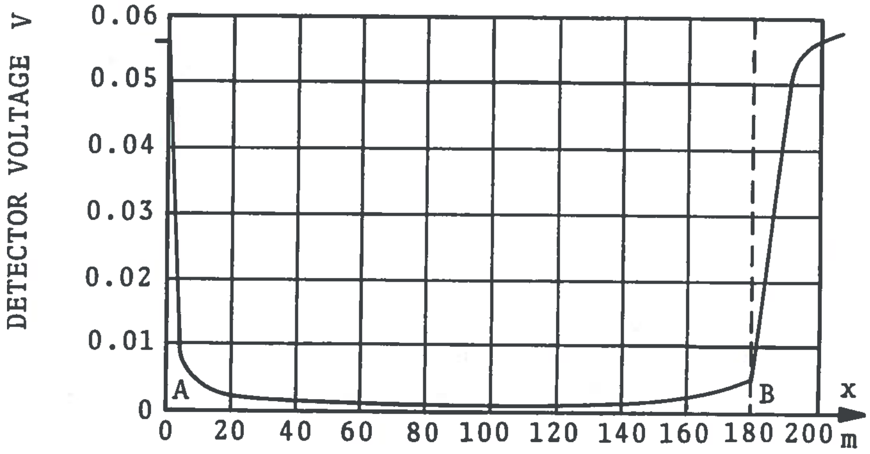
Z_L	Series impedance per unit length of track.
G	Conductance (per unit length) of ballast - earth path between rails.
Z_o	Characteristic impedance of the track.
R_g	Generator circuit impedance.
L	Inductance per unit length of track.
R_r	Detector circuit impedance.
R_A	Rail to rail resistance through axle of train (includes wheel contact resistance).



Note: Influence curves V(x) of a track circuit with current detector R_r = 1 ohm, 1_{AB} = 50 m, F_1 = 20 kHz and generator resistance Rg = 0. R_A, the train shunting resistance, has values of 0.1 ohm and 0.5 ohm respectively.

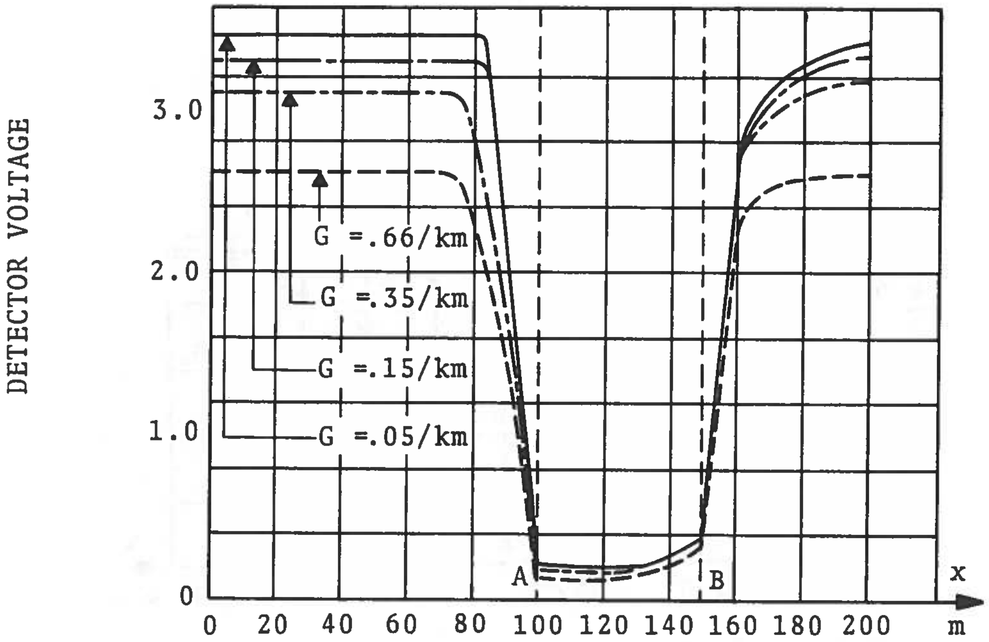
Figure B-11a Track Circuit Influence Curves
Sheet 1 of 4





NOTE: Influence curve V(x) of a track circuit with current detector R_r = 1 ohm, 1_{AB} = 180 m, F_1 = 20 kHz and generator Rg = 0. R_A, the train shunting resistance,is 0.1 ohm.

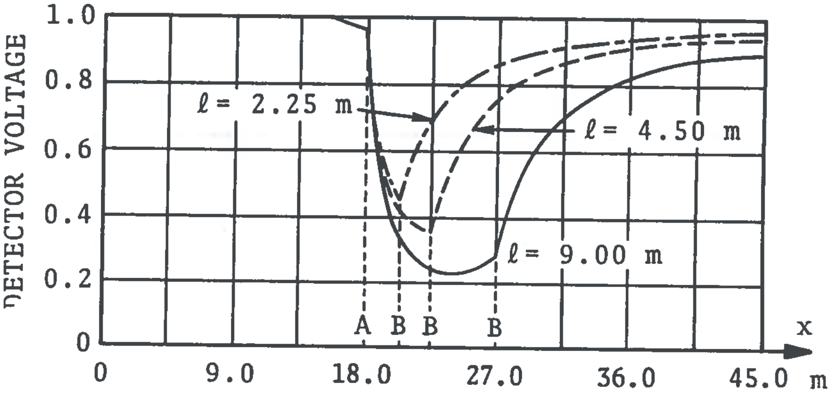
Figure B-11b Track Circuit Influence Curves
Sheet 2 of 4



NOTE: Variation of detector voltage V(x) for track circuit with current detector with several values of ballast conductance. Track length = 50 m, F_1 = 20 kHz, wheel-axle resistance R_A = 0.1 ohm, detector R_r = 1 ohm.

Effect of Ballast on Influence Curves

Figure B-11c Track Circuit Influence Curves
Sheet 3 of 4



NOTE: Influence curves V(x) of a track circuit with current detector R_r = 0.36 ohm, train resistance R_A = 0.1 ohm, section lengths of 9 m, 4.5 m, 2.25 m. F_1 = 20 kHz.

Effect of Short Lengths on Influence Curves

Figure B-11d Track Circuit Influence Curves
Sheet 4 of 4

ω Circular frequency of generation.

γ Attenuation. (nepers/unit length).

x Distance along the track from the start of the block.

V Voltage across the tracks measured at the detector.

I Current through the detector.

The rail configuration yields a negligible shunt capacitance so that for audio frequencies (greater than 1000 Hz) the series inductance is the only series element, and the ballast conductance is the only shunt element.

When excited by a voltage source, (generator), the current and voltage have a decremental loss due to the shunting effect of the ballast resistance and the voltage drop across the inductive reactance of the rails. This results in an attenuated traveling wave propagating down the track. The characteristic impedance of the track is $Z_0 = \sqrt{j\omega L/G}$ and the attenuation is, $\gamma = \sqrt{\omega LG/2}$. The voltage along the track has the form $V = V_0 e^{-\gamma x}$.

The series inductance for a five-foot spaced track is approximately 400 microhenries per 1000 ft. Figure B-12 is a display of the attenuation as a function of ballast resistance and frequency. The ballast conductance commonly used for design standards does not exceed 1/5 mho per 1000 ft. The actual ballast conductance is dependant on several factors, two of which are of concern here.

1. Water content of ballast
2. Surface condition of tie

The ballast conductance is a variable depending on the weather. The block must be made short enough so that the attenuation shown in Figure B-12, suitably modified by the arrangment of impedances in the detector and generator, does not cause a variation of the unoccupied block signal strength to be interpreted as attenuation due to train occupancy of the block. This must be done for all

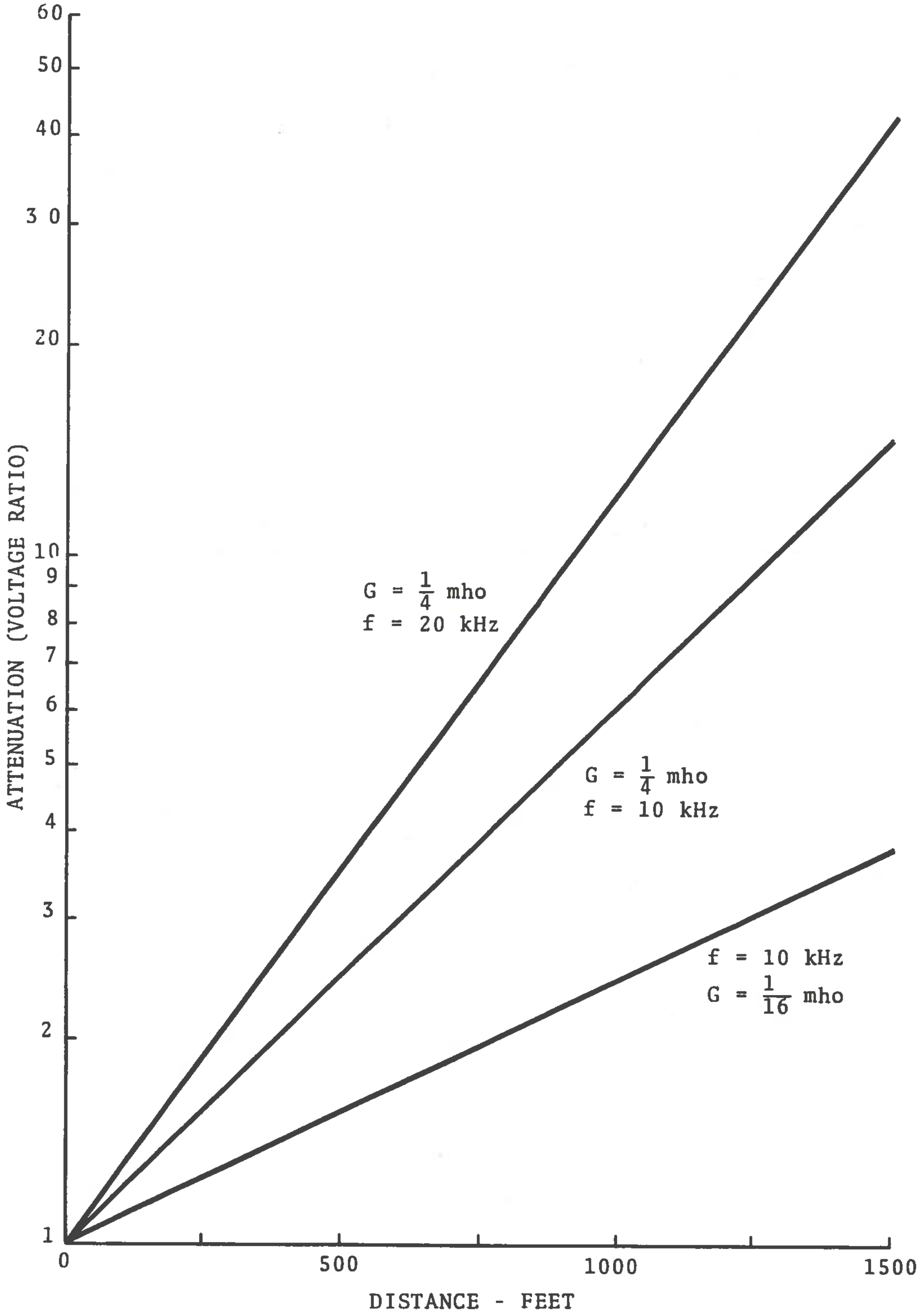


Figure B-12 Attenuation as a Function of Ballast Resistance and Frequency conceivable weather conditions. Figure B-11a is a plot of the received signal in a 50 meter track section with $R_g = 0$, $R_r = 1$ ohm and R_A having values of 0, 0.1 and 0.5 ohms. The curve is calculated from the reflections at A and B. The decrease of the attenuation caused by R_A at x as the value of R_A approaches the value of R_r can be seen.

It might be pointed out here that a generator having a high impedance is called a current generator. A low impedance makes it a voltage generator. A high impedance in the detector circuit makes it a voltage detector and a low impedance, a current detector. The relative values of the ballast, generator, wheel-rail and detector impedances affect the total attenuation and the range of influence of the attenuation on both sides of each generator and each detector.

The effect of ballast resistance decreasing in wet weather can be mitigated by using a voltage generator and a current detector which tends to minimize the variation of attenuation for a clear block as the ballast varies from wet to dry (see Figure B-13). It can be seen that the range of influence at the block boundary is decreased by lowering the wheel axle resistance, R_A, and further consideration shows that lowering the detector resistance, R_r, lessens the influence outside the block at that boundary. Figure B-11b shows the influence curve for a longer track section l_{AB} = 180 meters, at 20 kHz. Figure B-11c shows the effect of changing the ballast leakage for a 50 meter block. The slope of the influence curve is not affected so that there is not any loss of accuracy in position location assuming adequate signal-to-noise ratio. However, if the threshold must be set at a high level, (a common value is 40% of the unoccupied block signal), there is the possibility of conductivity changes giving false occupancy signals. Figure B-11d shows influence curves at 20 kHz for very short track sections of 9, 4.5, and 2.25 meters.

Neglecting the eddy current losses in the track it can be seen that the inductive reactance at 10 kHz for a 1000 foot section is 24 ohms. The ratio of generator to detector voltage for such a section having a ballast resistance of 16 ohms is 2.45, (see Figure

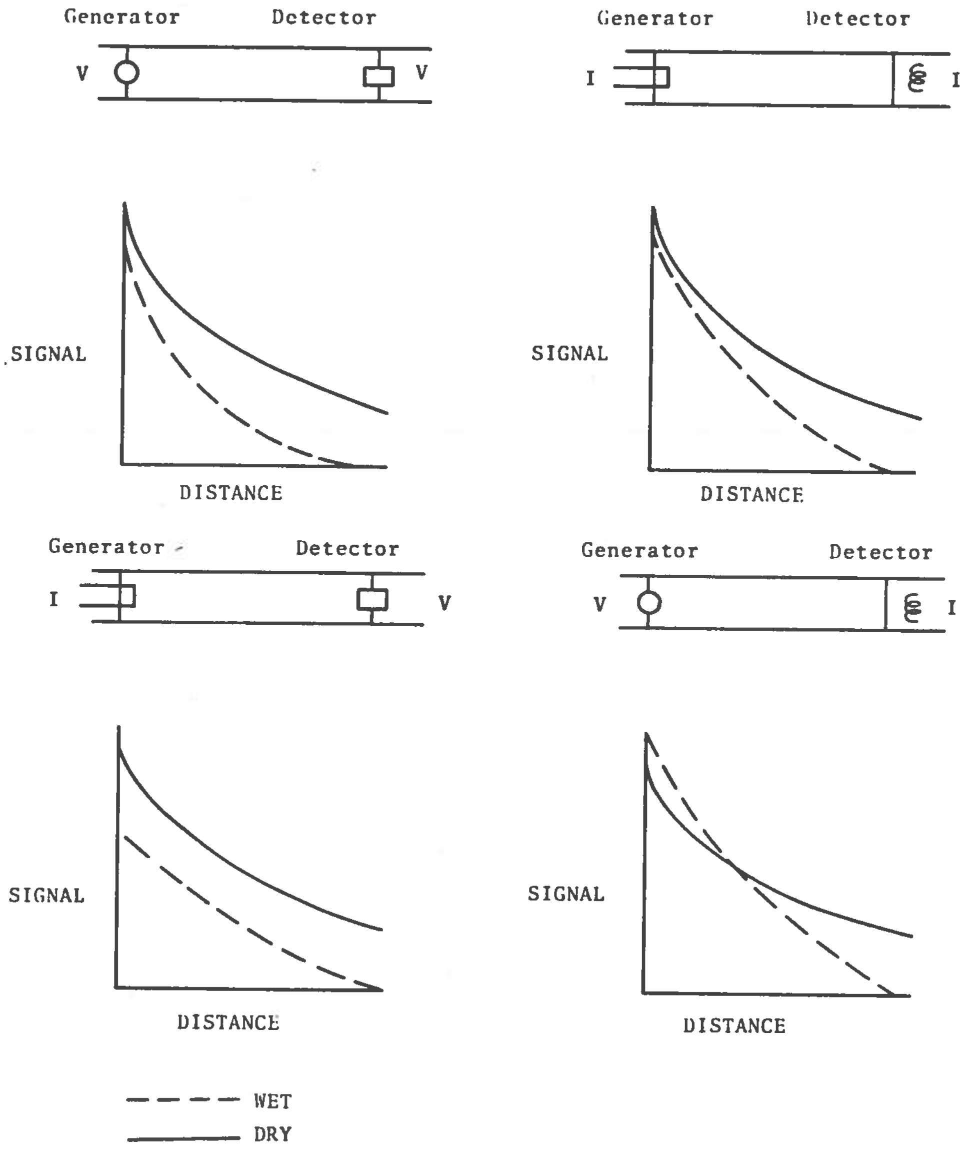


Figure B-13 Wet and Dry Attenuation for Combinations of Voltage and Current Generators and Detectors

B-12). Wet ballast brings about an increase in signal attenuation. A large variation of wet-to-dry received signal produces the same effect as a shunting axle and can generate false occupancy signals. For a fixed ratio of dry-to-wet conductivity the ratio of dry-to-wet received signals increases as the dry signal attenuation increases. It is for this reason that the signal attenuation in dry weather must be small. The contributing factors to good operation are well designed, low conductivity ballast, low frequency signals, and short blocks.

It has been shown, Figure B-11d, that a short block under some circumstances can result in such a small decrease in signal, due to the shunting value of a particular wheel-set, that the detection circuit must work at a high threshold level. The value of R_A, the wheel-track resistance, must be small in a track circuit with low ballast resistance and this must be considered in the vehicle and track design. For very short blocks in switch areas, insulated tracks are often used, allowing higher generator and detector impedances and correspondingly higher wheel-track resistance. For longer blocks of insulated or continuous track sections at audio frequencies, the same factors of G and Z_L require low wheel-track resistance and low generator resistance.

The track circuit also serves to convey control information from the wayside to the train, frequently by the same generator used for block occupancy signals but at a different frequency. The train can also reply to the wayside if it has a suitable transmitter. The problems of attenuation and interference for this link are similar to those of the occupancy circuits. The signals used for occupancy detection and to transmit control information to the train, convey information via frequency or amplitude-modulated carriers. A digital code is frequently employed as the modulating signal. This a generalized version of the original coded track circuit which consists of on-off modulated direct current controlling long time constant relays.

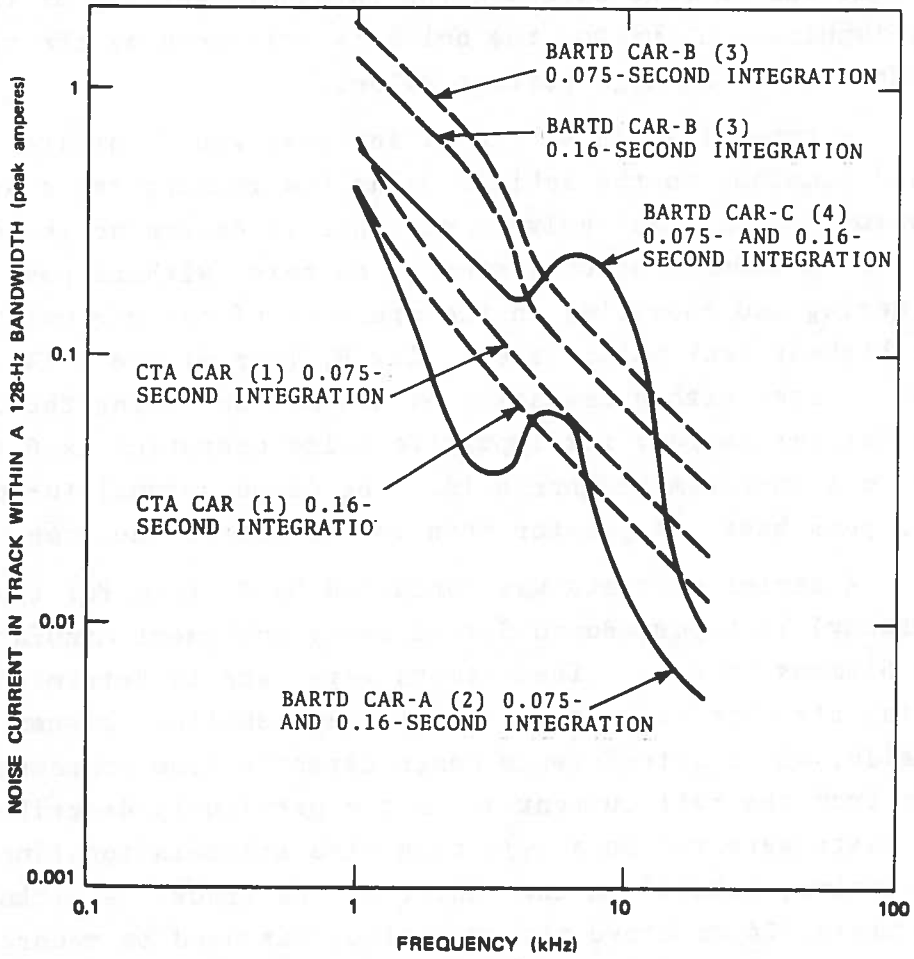
B6. INTERFERENCE

The successful operation of both the train surveillance system and communication system requires that error rates be maintained at a suitably low level. This requires a detailed knowledge of the interference environment, unfortunately not usually available. It also requires that controls be placed on all equipment which contribute to the interference (noise) environment and used in the vicinity of the trackage. Finally, it requires cooperation between general equipment designers and communications equipment designers in order to minimize the impact of one type of equipment on the other.

Analytical studies and empirical data are abundantly available for aerospace and commercial communications applications but are sparse for rail applications. The following discussion is therefore limited to some measurements made by General Electric Research and Development Center and the Institute for Transport of Brunswick Technical University.

The G.E. studies were made of running rail noise currents produced by propulsion equipment in electrified rail rapid transit systems on the Chicago Transit Authority and on the Bay Area Rapid Transit District test track at Concord, California. The recordings cover the band from 100 Hz to 24 kHz. Four propulsion systems were included: switched DC at 600 volts, chopped DC at 1000 volts, chopped 3 phase AC at 4160 volts converted to DC, and rectified 3 phase AC at 4160 volts converted to DC and then chopped to AC. Recordings were made by suspending coils from the front of the car, one above each rail, and measuring the induced voltage.

The distribution of currents into random noise and spikes can be estimated from the tails of the spectral distributions. Figure B-14 shows the spectral distribution from which the general observation can be made that noise levels in the region below 10 kHz make it a difficult region for operation of a communications system.



NOTE:
1. CTA 600 volt DC switched resistor
2. Car A 4160 volt 3 phase AC-DC
3. Car B 1000 volt DC chopper
4. Car C 4160 volt 3 phase AC-DC

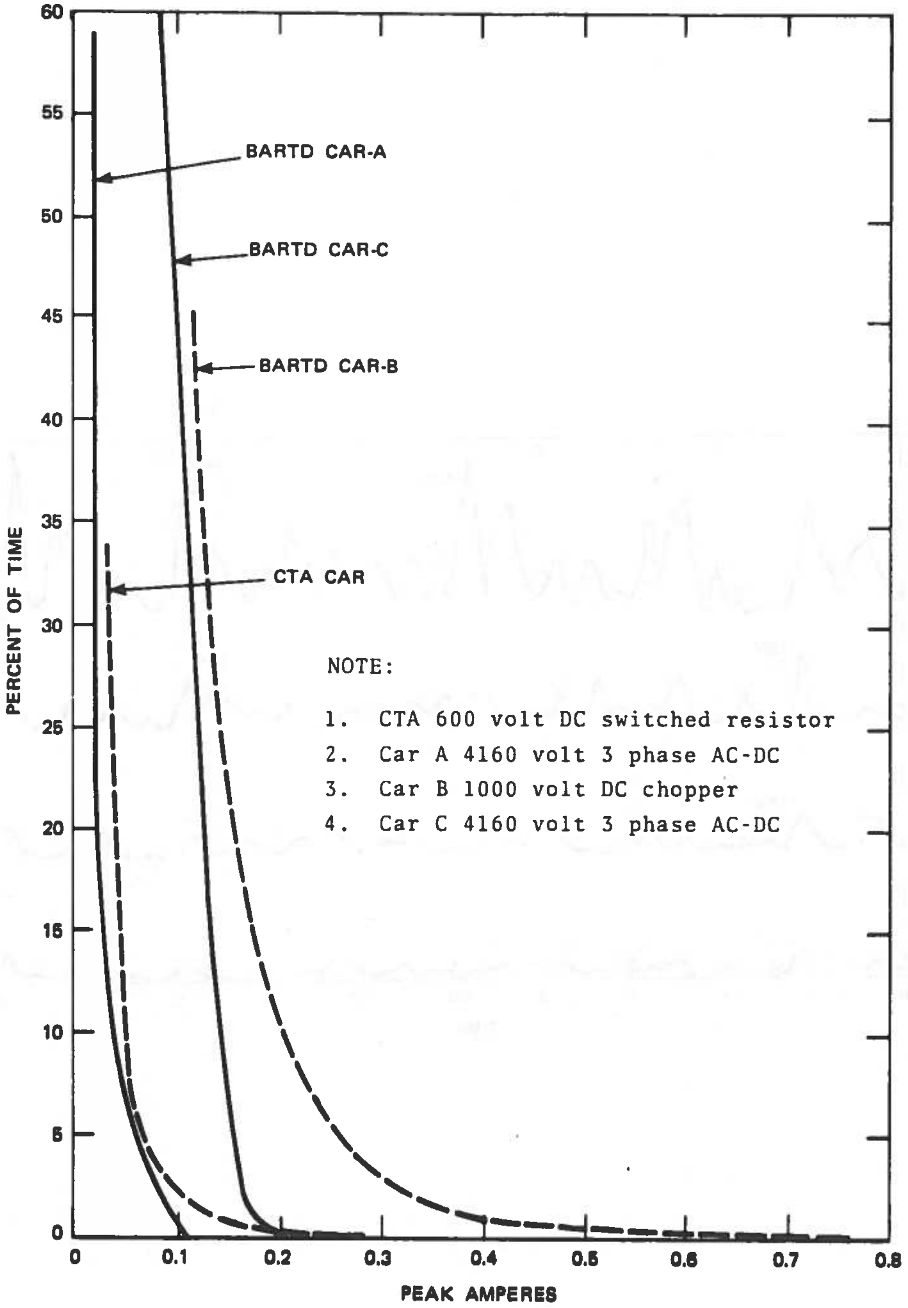
Figure B-14 Noise Currents in Track Versus Frequency for Four Propulsion Systems

Figure B-15 was obtained by passing the recorded noise through a 600 Hz bandwidth filter at 4900 Hz and measuring the fraction of time the current exceeded the threshold setting of the detector. The impulsive nature of the noise is evidenced by the tailing out of the curves at high current values.

A communication system of interest would involve transmitting speed commands to the vehicle using the running rails as a transmission medium. An analysis was made to determine the requirements for an FM communication system to do this; without post-detection-filtering and operating in the presence of one car which produced the highest peak noise levels, Car B, (see Figure B-14). For a 5 kHz system with a deviation of 300 Hz, and using the Car B data, the carrier current for impulsive noise operation is 0.72 amperes for full improvement threshold. The output signal-to-noise ratio on a peak basis is greater than 16 for 99% of the time.

A series of tests was conducted by P. Form for the Hamburg (Germany) Transport Board System using equipment manufactured by the Siemens Company. These tests were made to determine the effect of interference on systems inductively coupling between vehicle and wayside, where interference comes directly from components rather than from the rail current as in the previously described tests. The tests were run on a twin open wire transmission line, with a 10 cm spacing, located in the center of the track. A pickup coil on the train, 26 cm above the twin line, was used to record interference voltages. The coil was calibrated employing audio frequency power fed into the twin line. The propulsion equipment consisted of 800 volt DC motors.

Figure B-16 shows data on several frequencies, taken with a 2.5 kHz filter, again showing the rapid decrease of interference with increasing frequency. In these tests the greatest part of the interference was caused by the train itself, shown by the fact that test made at a distance from the train, with the track carrying current, generated little interference.



NOTE:

1. CTA 600 volt DC switched resistor
2. Car A 4160 volt 3 phase AC-DC
3. Car B 1000 volt DC chopper
4. Car C 4160 volt 3 phase AC-DC

Figure B-15 Amplitude Probability Distribution in the Band 4600 Hz to 5200 Hz

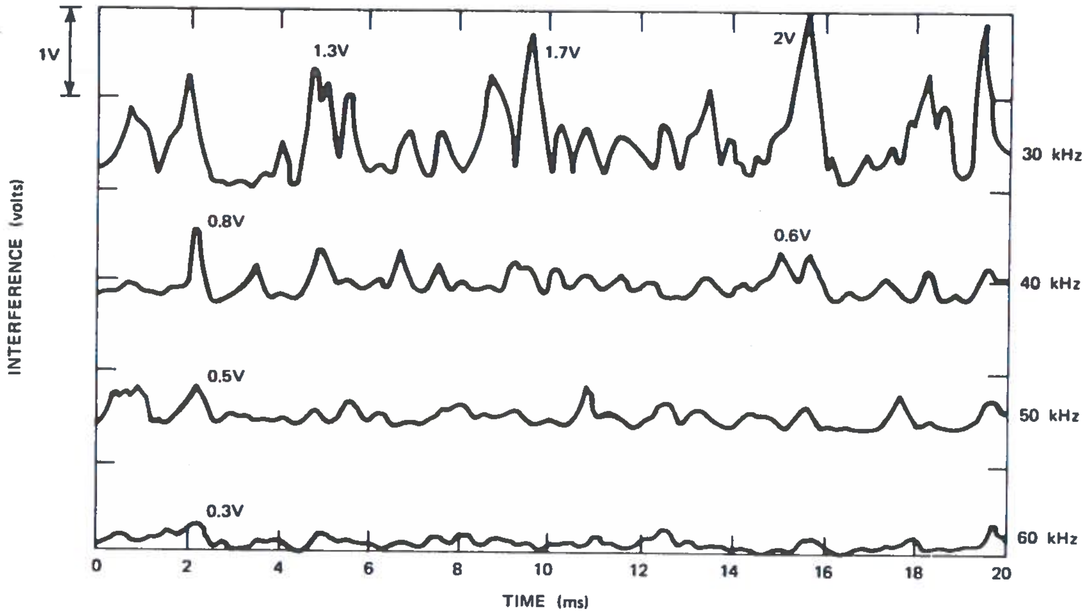


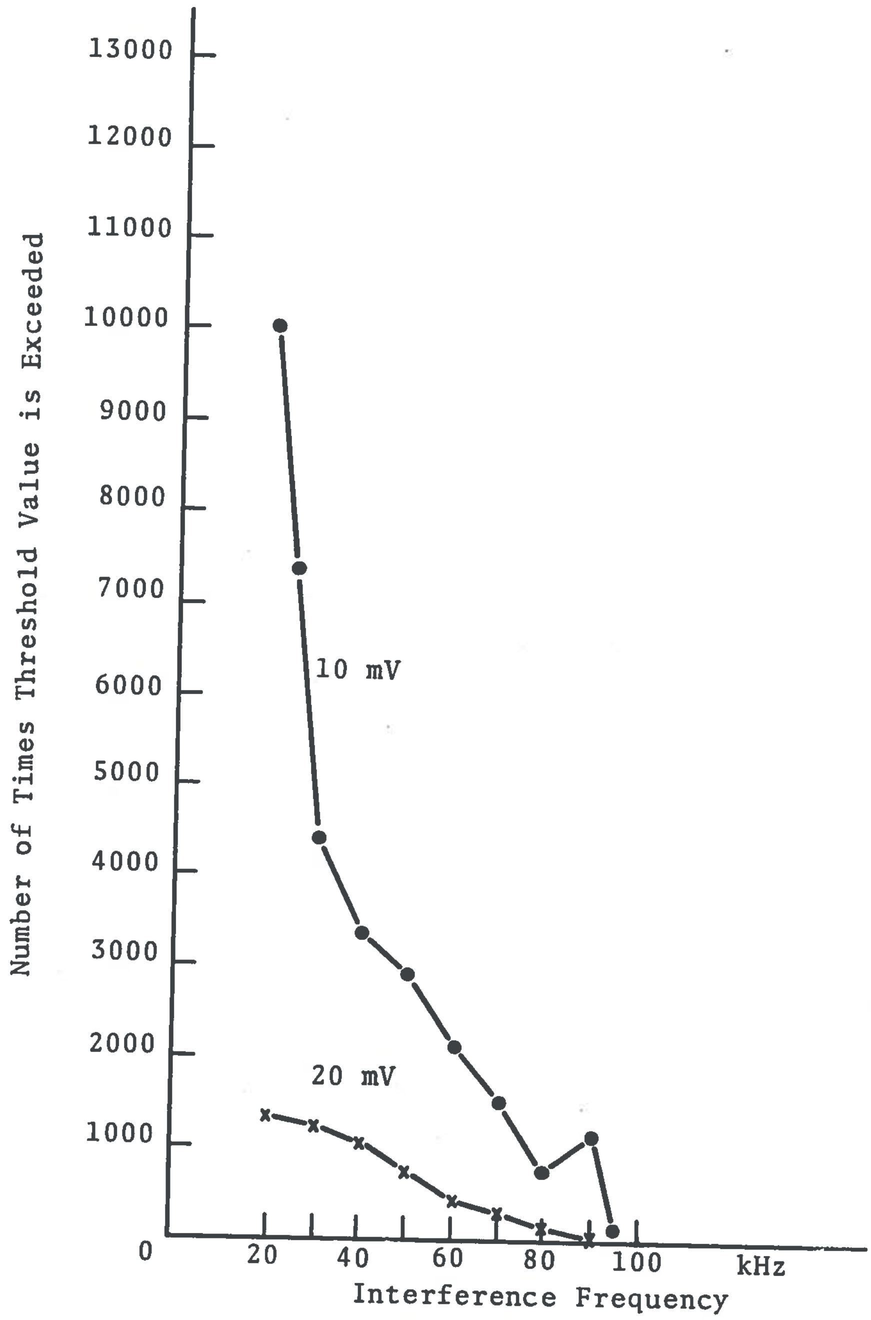
Figure B-16 Interference Pulses Caused by Change of Rail Current

Figure B-17 shows the number of pulses exceeding 10 mv and 20 mv respectively as a function of frequency (20 - 95 kHz). The pulse levels of 10 mv and 20 mv correspond to the following power levels in the twin line calibrating signal.

	Power Levels	
Frequency	10 mv	20 mv
20 kHz	5.4 watts	21.5 watts
30 kHz	2.4	9.6
40 kHz	1.35	5.4
50 kHz	0.86	3.5
60 kHz	0.6	2.4

Very little interference above 100 kHz was observed in the experiments.

Figure B-18 shows the pulse effects of change of current in another type car again using 2.5 kHz filters. The use of high frequencies is strongly indicated but in addition a very detailed study of each property interference environment is required to meet the interference problems and to provide the data base to aid in designing future systems. In designing for a new property it is necessary to establish standards for the electromagnetic fields generated by all equipment that will be used in the vicinity of the rails. Moving the communications to higher frequencies will eliminate many potential conflicts and limitations presently affecting wayside equipment.



NOTE: Duration of observations: approx. 12 minutes.
Parameter: interference amplitude.

Figure B-17 Analysis of Interference Phenomena Recorded with the DT 1 Motor Car

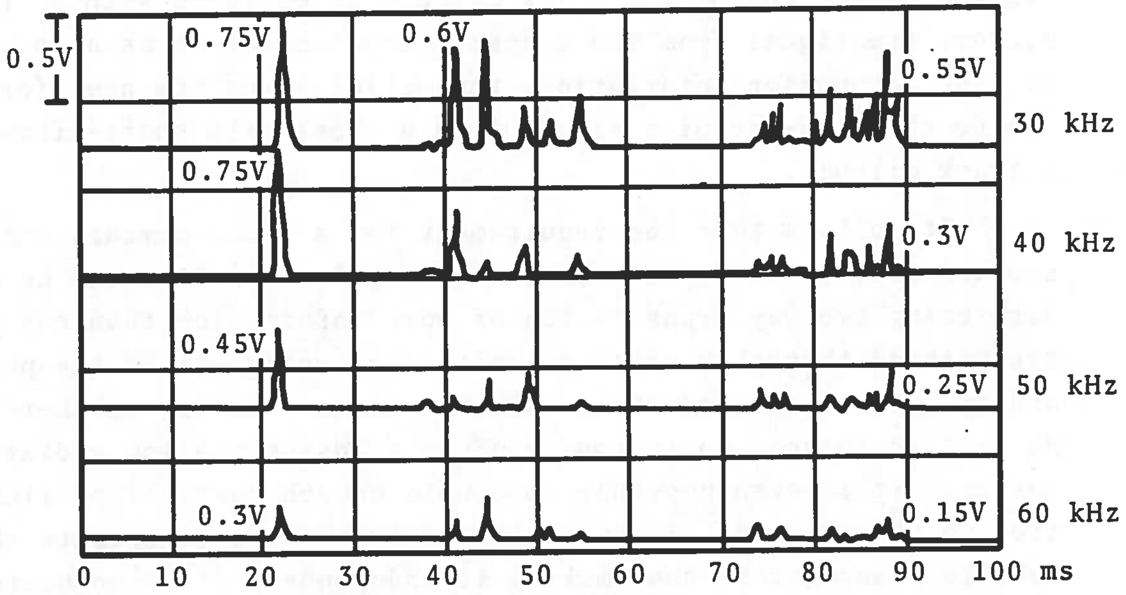


Figure B-18 Interference Pulses with Greatly Different Spectra (Change of Rail Current, DT 2-3 Motor Car)

B7. INDUCTIVE SYSTEMS

Two way transmission between the vehicle and a line-side control point permits the use of a complete feed-back control system. With continuous monitoring of the train position, it is possible to better meet the requirements for safety in a signaling system. With two-way transmission using track circuits, the information exchanged between the train and control point is limited by the attenuation, which increases with increasing frequency. If the vehicle occupying the track circuit is equipped with a transmitter, the signal from the transmitter also serves as a source of line occupation information, thus eliminating the need for deriving the line-occupied signal from a wheel-axle short-circuiting a track circuit.

It follows that the requirement for a track circuit can be avoided and, instead, an inductive communication line can be used, permitting two-way transmission of more information than can be transmitted through a track circuit. In such a system the position and spacing of the inductive line can be controlled, so there are no ballast losses, no ferrous conductor losses and low radiative losses. It is even possible to couple enough energy from line-side to the vehicle, via an auxiliary frequency, to operate the vehicle transmitter, thus making it independent of an on-board power source. This makes continuous position monitoring of a "dead train" possible.

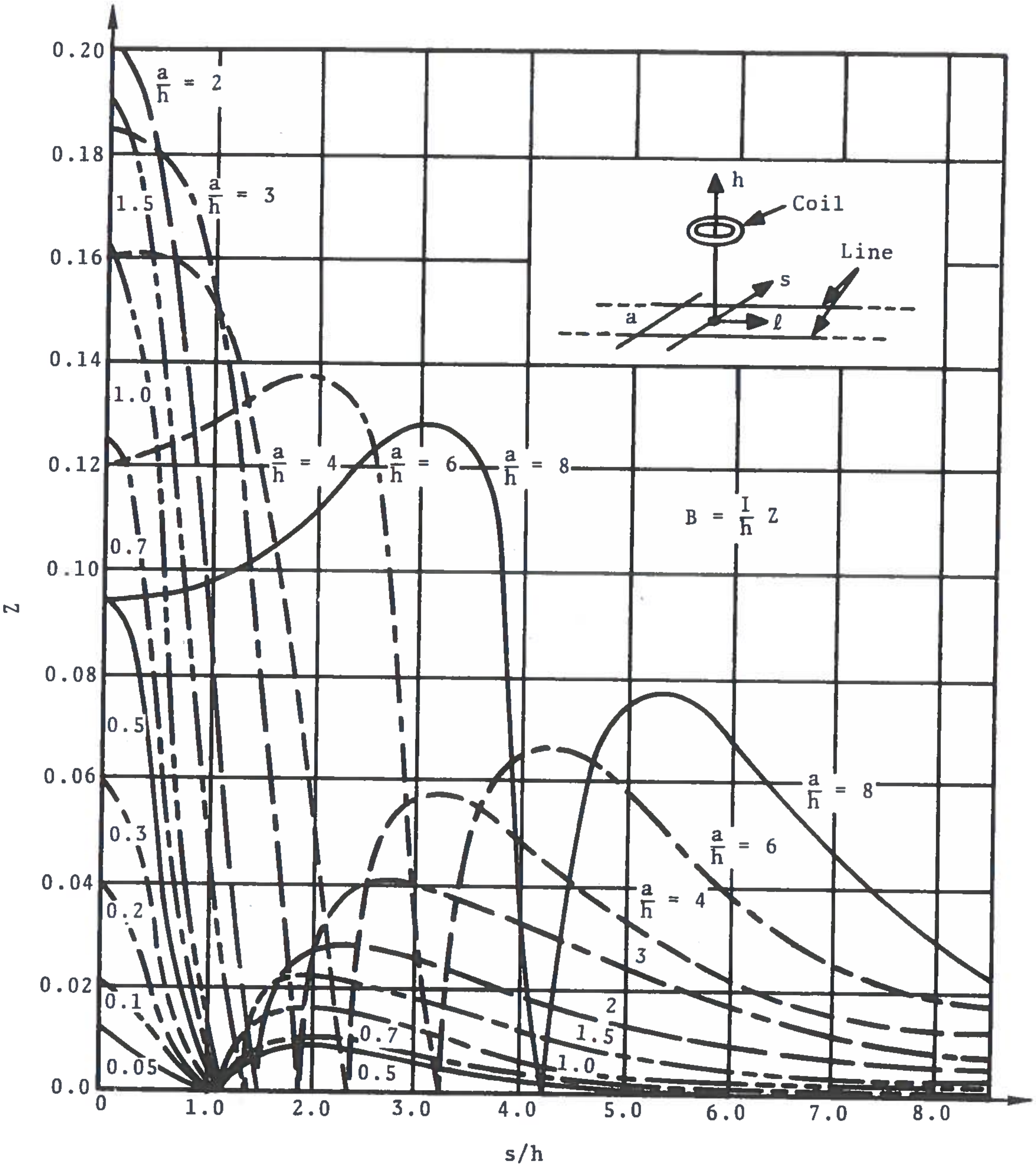
Point-to-point radio communication is a conventional approach to this control problem, but atmospheric variations and crowded spectra preclude the degree of reliability required. A leaky guided-wave system would work as well as an inductive system, but it is inherently more complex and at present, more costly so that it appears natural to consider the inductive system first.

The foregoing indicates that frequencies in excess of 100 kHz may be necessary to avoid propulsion current noise. Now consider an unshielded twin conductor line placed by the side of or between the rails so that a vehicle-mounted coil can be inductively coupled to it. The coupling depends on the line spacing, a, the height of the vehicle receiver above the line, h, and the lateral distance between the vehicle mounted loop and the center of the line, s. The spatial variation of the vertical component of the magnetic induction field, B, for a line current, I, is shown in Figures B-19 and B-20. The forms are intuitively expected, but give a comfortable range of placement of line and coil.

Figure B-20 shows the variation of magnetic field in the horizontal plane at various heights above the track. For $h/a<1$, i.e. for train pick-up coils at altitudes less than the line width, the flatness of the curves make the system relatively insensitive to coil position.

The twin line characteristic impedance can be stabilized and attenuation can be reduced, especially in wet soil, by using a relatively thick dielectric jacket. Figure B-21 describes the frequency dependence and the influence of the rails on a system in which the line is centered between tracks. The attenuation is shown in millinepers per kilometer (one neper corresponds to a decrease in signal by a factor equal to the Naperian base, e). Stranded wire of approximately 0.1 inch diameter with a dielectric coating of about .020 inches was used for the tests with the dielectric thickness increased by a factor of 5 for plot (3b). For a line mounted on the ties, the attenuation is extremely low and is unchanged for conductor spacing ranging from 4 inches to 44 inches. Note that plot (1a) should be used as the result achievable, since, by suitable mounting, the ballast effect can be eliminated. Plot (b) shows that the line can be laid on the flange of the rail itself and while the attenuation increases because of ferrous losses in coupling to the rail, this attenuation is modest, even at 100 kHz, if the dielectric is thick enough.

Tests have been made on coaxial-type three conductor cable which consists of a conventional coaxial cable over which a dielectric sheath is bonded and lapped by a conducting spiral, the whole sheathed in a second dielectric layer. The cable is



NOTE: Diagram to determine the vertical component of the magnetic induction $B = (I/h)Z$ as a function of the side distance/height ratio, s/h, with the core distance/height ratio, a/h, as a parameter.

Figure B-19 Magnetic Induction (Vertical) Over Rails

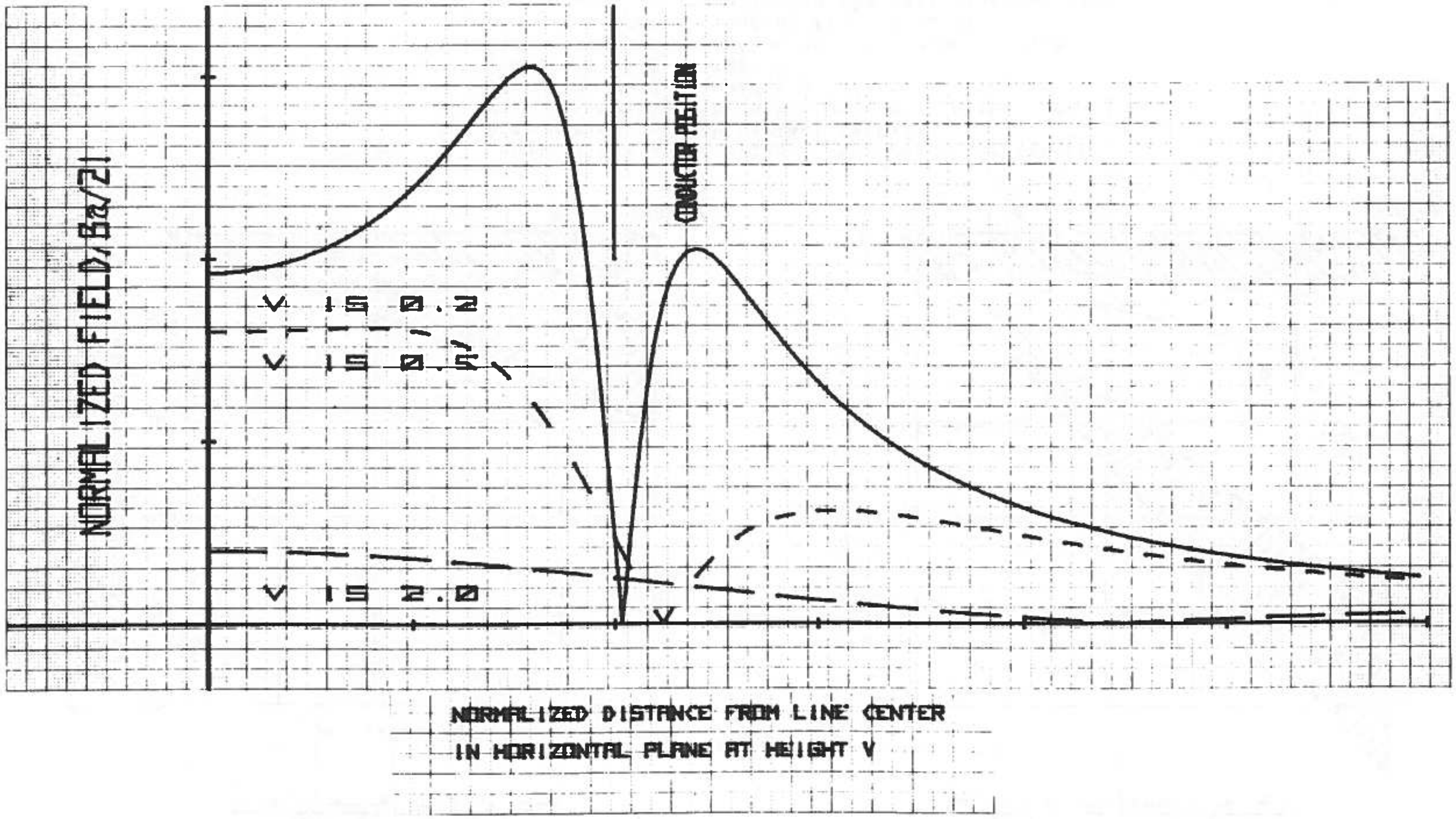
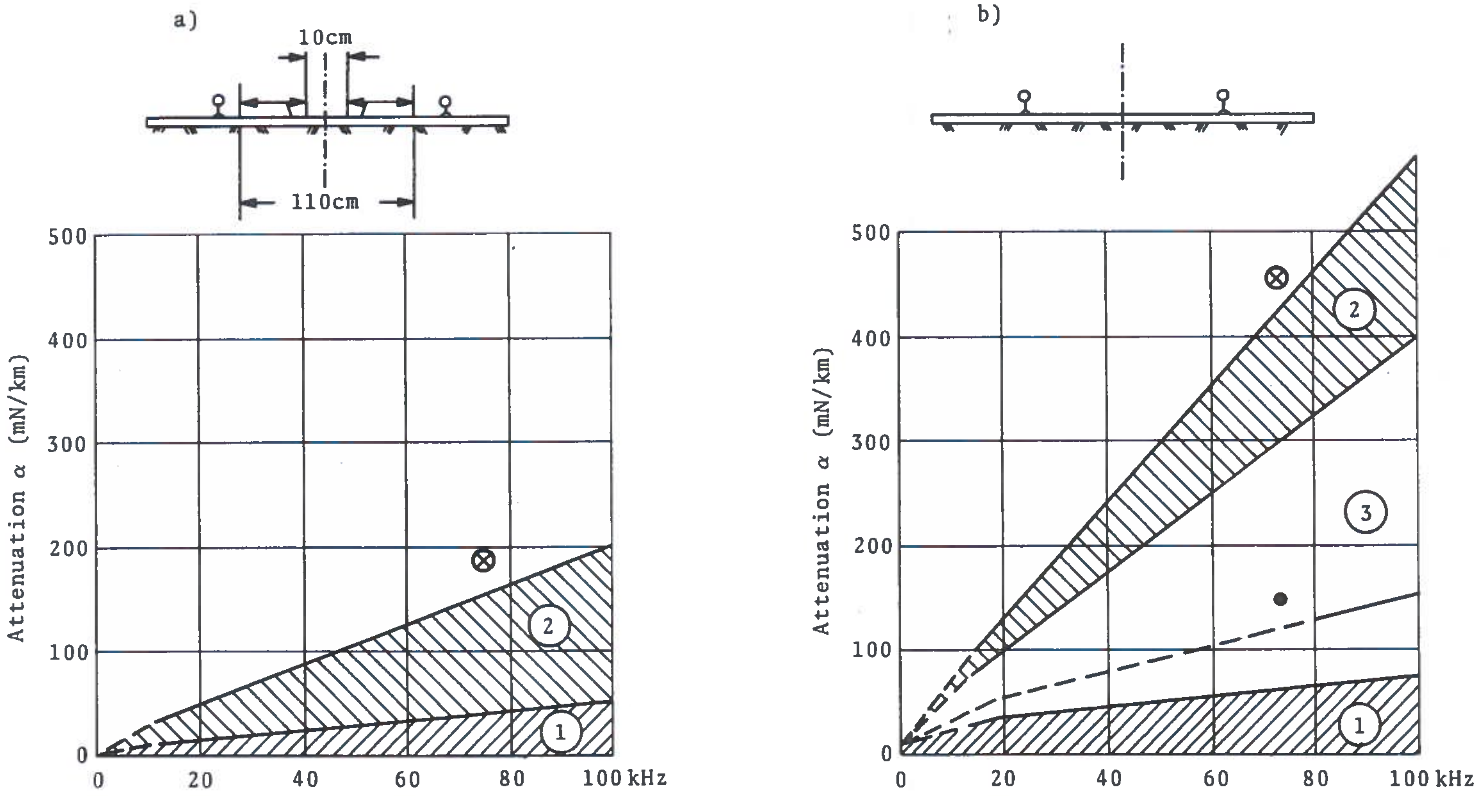


Figure B-20 Field Above Twin Line as a Function of Normalized Height



NOTES:
1. Longitudinal attenuation of the conductor itself.
2. Attenuation through ballast leakage.
3. Rail attenuation through coupling with the line conductor (additional longitudinal attenuation caused by eddy currents).

(a) Line conductor installed on the sleepers, with conductor spacing ranging from 10 to 110 cm.

(b) Line conductor installed on the rail flanges, with conductor spacing of 143.5 cm.

⊗ Stranded wire conductor 2.7 mm O; external diameter 4 mm dielectric.

● Copper conductor 2.2 mm O; external diameter 9.5 mm.

Figure B-21 Attenuation (α) as a Function of Frequency, for Different Positions of Track Line Conductance shown in Figure B-22. As it is employed in inductive signaling, a signal is applied between the outer conducting sheath of the coax and the spiral conductor. The center conductor is used for conventional coax applications.

Figure B-23 shows the signal strength measured 100 feet distant from a cable of the foregoing type buried 30 inches deep in soil. The cable was 2600 feet long and power to the terminated cable at 525 kHz was 1.17 watts. No appreciable attenuation was observed but there is no information available on the effect of ground condition and moisture. The variation of signal strength with lateral position, shown in Figure B-24, gives a field strength of 0.1 volt/meter at trainside for such a buried cable carrying 0.73 watts at 540 kHz.

From the preceeding, it is evident that two way transmission of information between train and line at high frequencies is practical. This system can be modified to mark prominent points of the line. By crossing the conductors at fixed lengths a most useful modification is obtained since each crossing point is not only a position of zero field but the position of a discontinuous 180 degree phase shift of the field. These two effects permit discrimination of perturbations to nearby metallic structures which otherwise would affect the null position.

At a crossing point, with a suitable configuration of coils, the null of the vertical component of field can be detected while still using the horizontal component for communication. This is illustrated in Figure B-25.

In summary, the vehicle measures its position by detecting the crossings and transmitting them to the wayside (or to Central). All information relating to control of the vehicle can be exchanged at all levels of control, via the line. One very useful variation is the use of auxiliary wayside transmitting loops (not coupled to the line) which are activated via the line to deliver local signals (see Figure B-26).

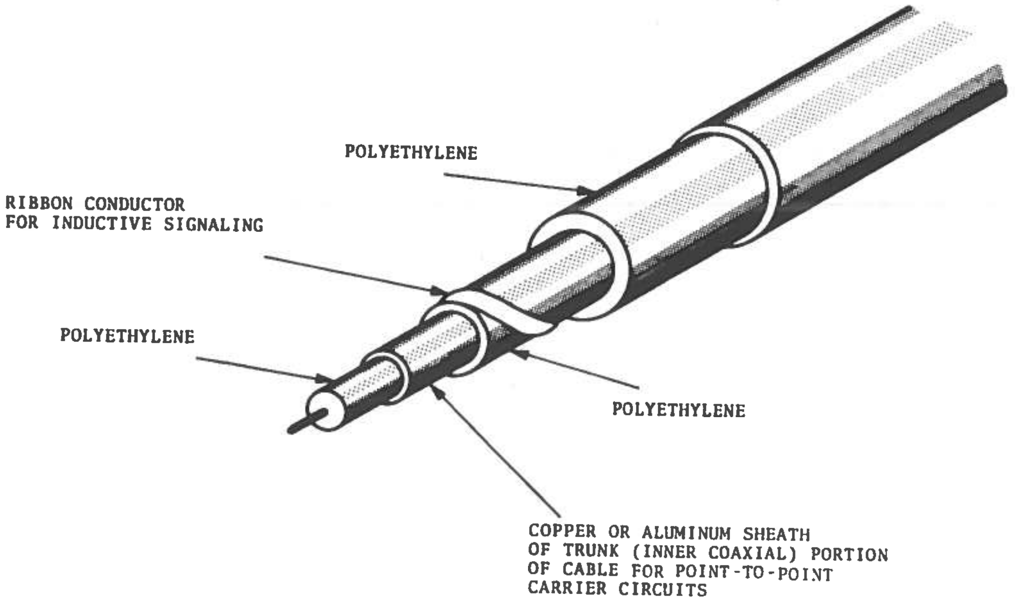
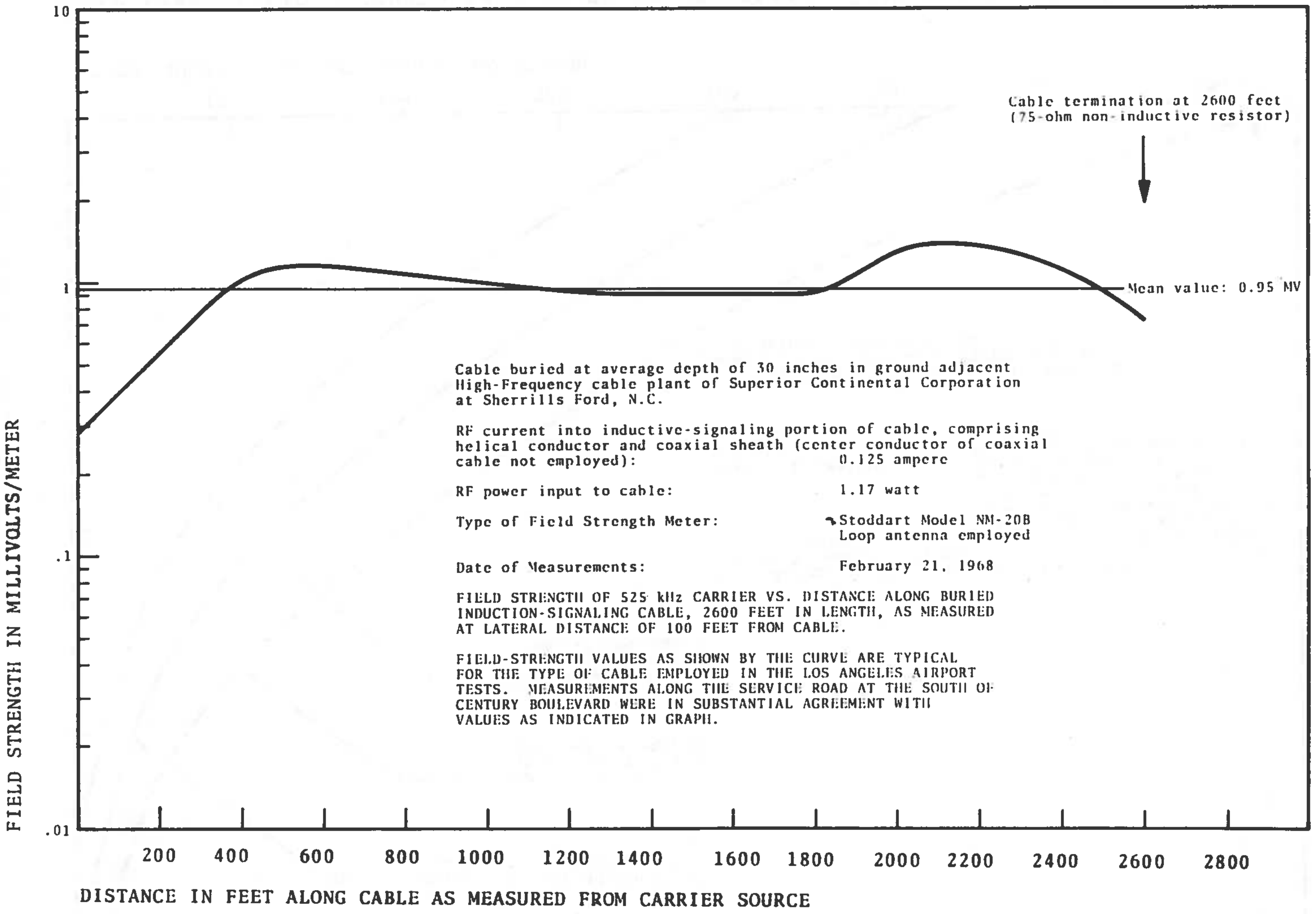


Figure B-22 Coaxial Cable for Broadband, Point-to-Point Carrier Circuits



Cable termination at 2600 feet
(75-ohm non-inductive resistor)

Cable buried at average depth of 30 inches in ground adjacent High-Frequency cable plant of Superior Continental Corporation at Sherrills Ford, N.C.

RF current into inductive-signaling portion of cable, comprising helical conductor and coaxial sheath (center conductor of coaxial cable not employed): 0.125 ampere

RF power input to cable: 1.17 watt

Type of Field Strength Meter: Stoddart Model NM-20B Loop antenna employed

Date of Measurements: February 21, 1968

FIELD STRENGTH OF 525 kHz CARRIER VS. DISTANCE ALONG BURIED INDUCTION-SIGNALING CABLE, 2600 FEET IN LENGTH, AS MEASURED AT LATERAL DISTANCE OF 100 FEET FROM CABLE.

FIELD-STRENGTH VALUES AS SHOWN BY THE CURVE ARE TYPICAL FOR THE TYPE OF CABLE EMPLOYED IN THE LOS ANGELES AIRPORT TESTS. MEASUREMENTS ALONG THE SERVICE ROAD AT THE SOUTH OF CENTURY BOULEVARD WERE IN SUBSTANTIAL AGREEMENT WITH VALUES AS INDICATED IN GRAPH.

Figure B-23 Field Strength as a Function of Distance from Carrier Service

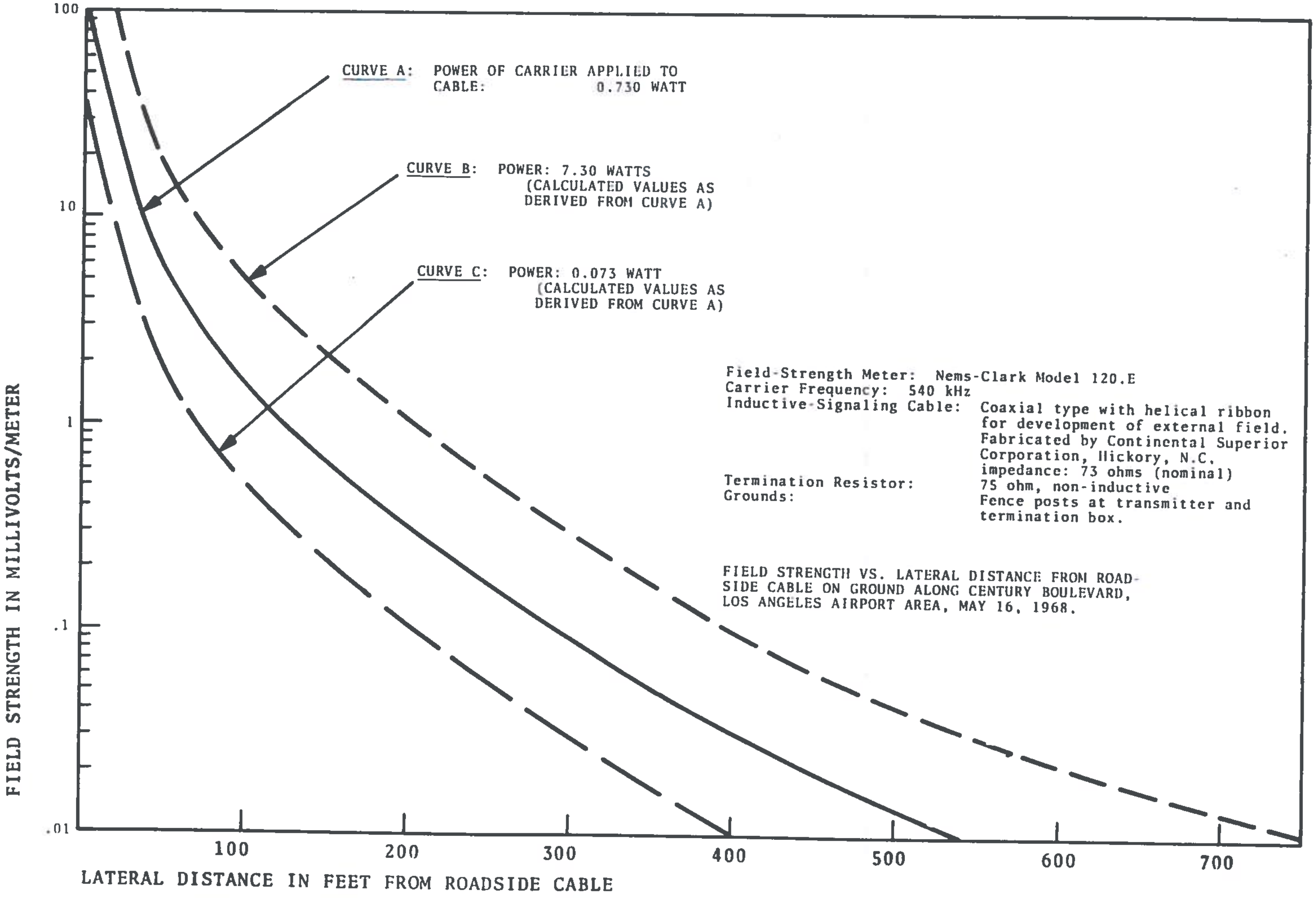
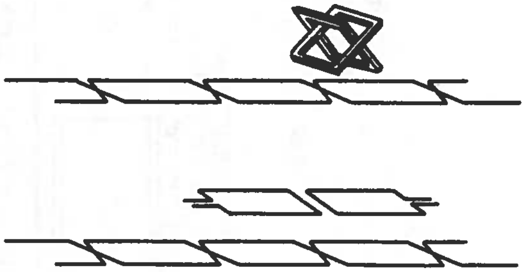


Figure B-24 Field Strength as a Function of Lateral Distance from Trackside Cable



NOTE: Arrangement of aerial for maintaining the transmission of information even when the vehicle has stopped above a crossing point.

Figure B-25 Antenna Arrangement

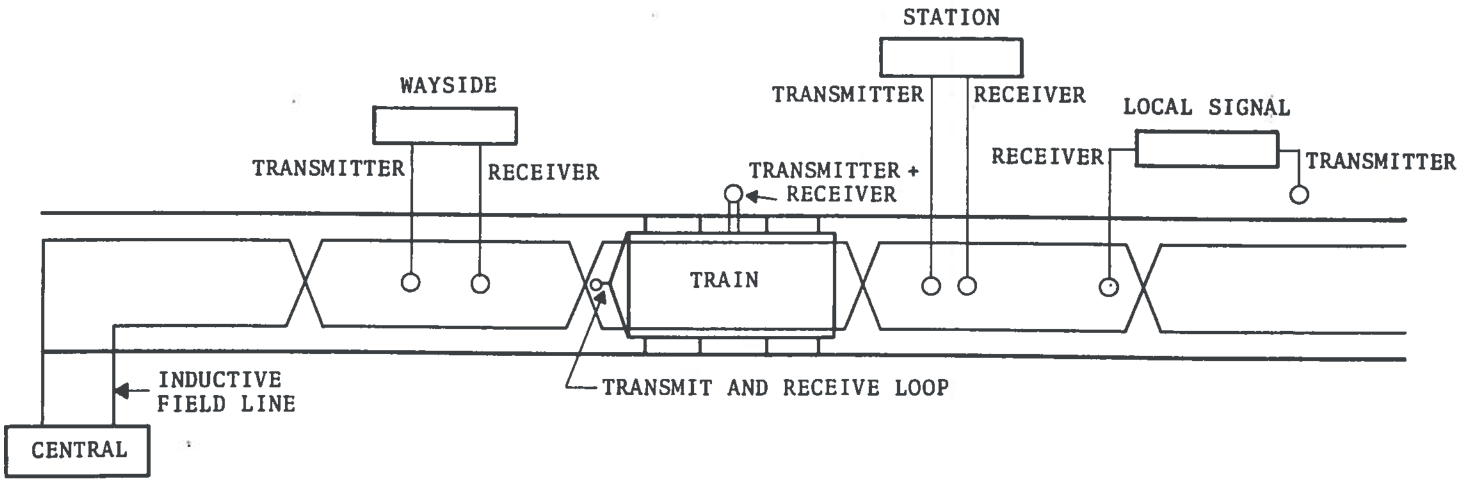
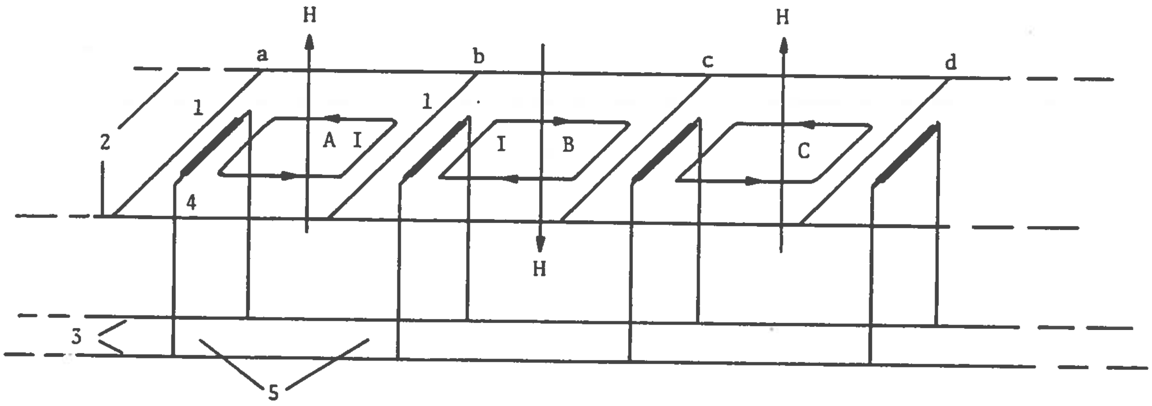


Figure B-26 Combined Inductive Surveillence and Communications System

Another interesting variation uses the twin conductor to feed shunted track blocks, thus using track circuits at high frequency to couple signals to the vehicle. This is possible because although losses prevent the track's use as a transmission line, controlled coupling from a lossless line to each block allows a small enough fraction of energy to be transferred to attain a suitable attenuation rate (see Figure B-27). An advantage of this system is that the line may be buried or otherwise protected so that it cannot be easily damaged.

A further possibility with twin lines is a phase scanning technique which has the virtue of giving continuous position information. (See Figure B-28). Two twin lines are laid along the track, two currents are fed to the system with one shifting in phase linearly in time so that a standing wave with a null travels along the line in one case, and in the other a difference in phase between the two lines is propagated. The train transmits a pulse when it measures a null, thus notifying the wayside of its position. The technique is well adapted to standard magnetic drum processing arrangements.

As an example of the foregoing phase scanning technique, a 500 kHz twin line, 1000 feet long with a phase shifter modulated at 10 Hz scans the line with a moving null every 1/10 second. The train responds with a 450 kHz signal upon receiving the null. The time elapsed between the beginning of the scan and the received null at the wayside gives, for all practical purposes, a continuous measure of position. This is an example of an analog method of position location in contrast to a system in which digital information is exchanged for verification of position. A combination system would have the train respond to the null with transmission of its identification.



NOTES: 1. Cross-conductors at points, a, b, c... of the track.
2. Rails.
3. Trunk line by the side of the track.
4. Transformer coupling between track loops and trunk line.
5. Connection point of track loop to trunk line - A, B, C = track loops.

Figure B-27 Principle of Track Loop Circuiting

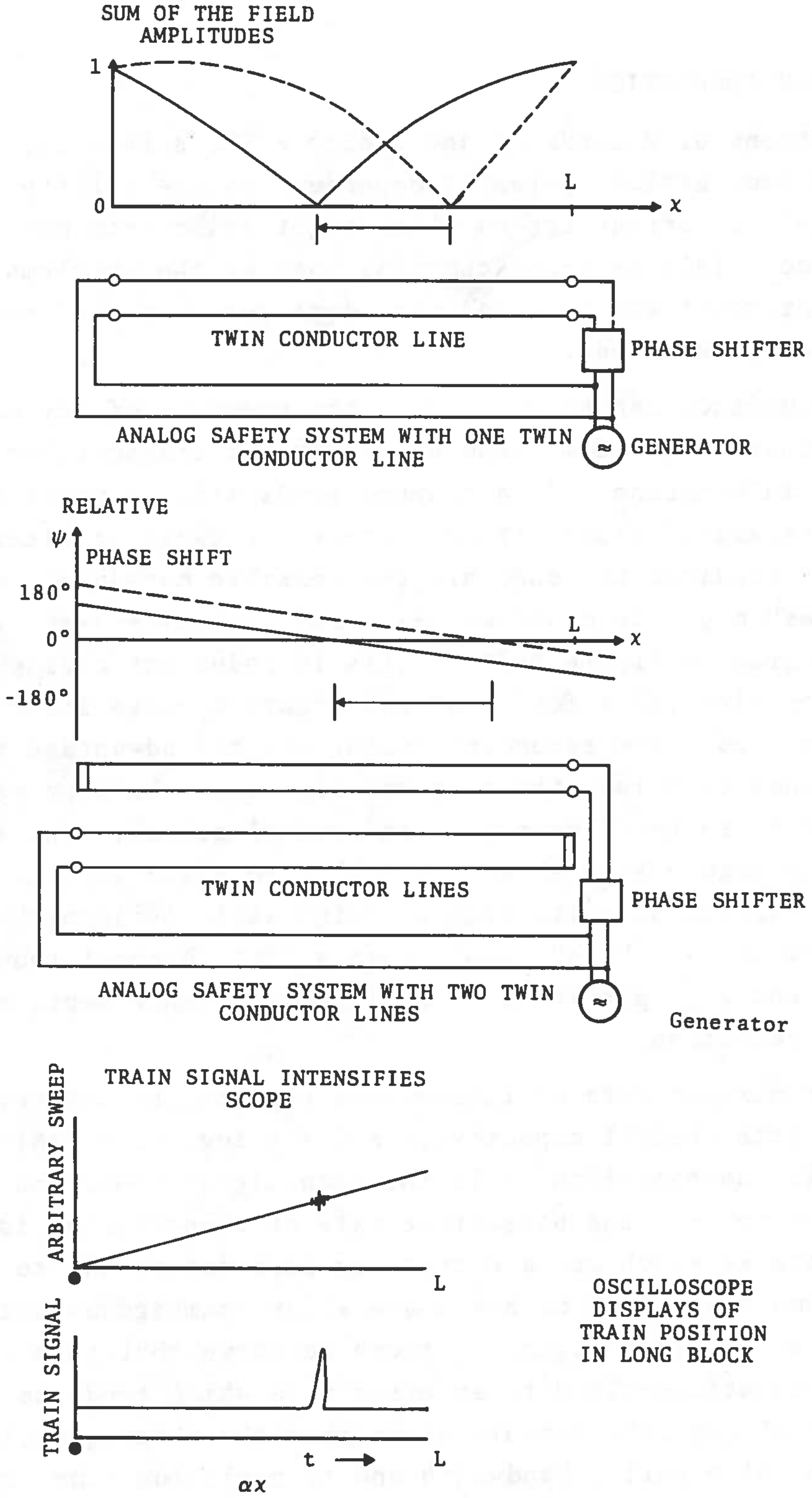


Figure B-28 Occupancy Detection by Moving Null on Resonant Transmission Line

B8. ERROR CORRECTION

Notions of Redundancy and Coding - The safety and reliability of the communication system is dependent on the ability to detect errors and to correct errors which might arise from noise and interference. This Section describes some of the problems arising from error considerations and considers remedies available to the communication engineer.

Redundancy can be defined as the presence of any message detail other than the minimum necessary for transmission of the required information. If a channel sends signals which are positive or negative pulses with no interval between (a binary channel), and it is required to send only two possible messages, "yes" or "no", "yes" might be coded as ++--- and "no" as +-+-+-. (See the first diagram in Figure B-29). This is redundant coding, as a simple positive pulse for "yes" and negative pulse for "no" could have been used. The redundant coding has the advantage that, in the presence of noise, the received signal can be correctly interpreted in spite of errors in individual pulses. The second diagram in Figure B-29 shows a possible received signal. A decision circuit of quite simple design will distinguish the processed signal as a "yes" rather than a "no". Without redundancy, a message sent at a particular time in this example would suffer an error in reception.

The maximum rate of information that can be delivered over a channel, (the channel capacity), is $C = W \log_2 [1 + P/N]$ bits/sec where W is the bandwidth, P is the mean signal power and N is the mean noise power. The noise-free rate of transmission is decreased by the rate at which extra correcting information has to be supplied to overcome the effect of noise and allow unambiguous interpretation of the received signal. It can be shown that this channel capacity is attainable with an error rate which tends to zero. This channel capacity formula shows that the three quantities, signal to noise ratio, bandwidth and transmission time, can be

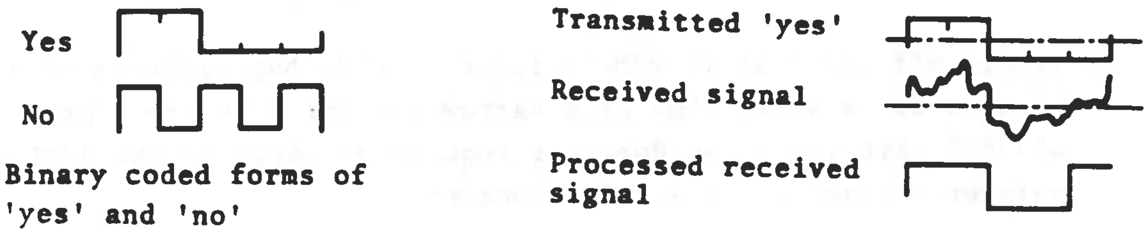
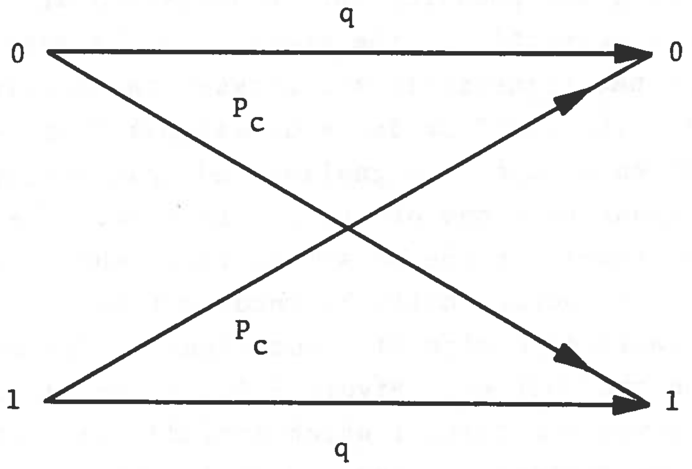


Figure B-29 Coding Waveforms



Note: q is the probability that a 0 or 1 will be correctly detected. pc is the probability that a 0 or 1 will be interpreted as a 1 or 0 (a crossover)

Figure B-30 A Binary Symmetric Channel

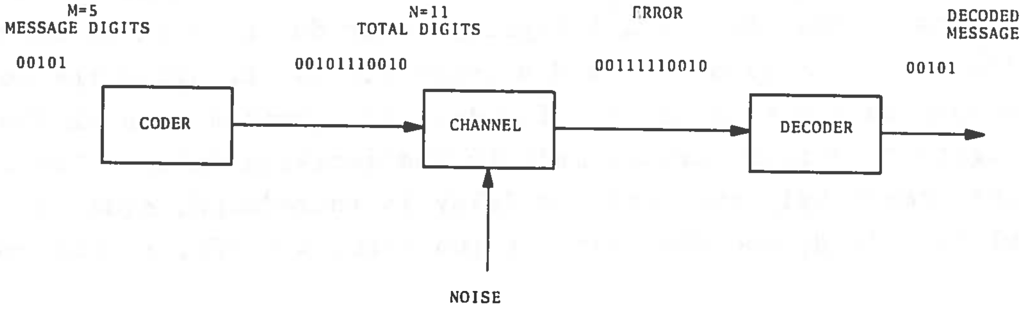


Figure B-31 Check-Digit Code for Binary Symmetric Channel traded off and that if P/N is fixed, a wide bandwidth channel may be used for a short time or a narrow one for a longer time. A channel with low noise does not require as large a bandwidth as a noisier channel for the same capacity.

It is difficult to give even a qualitative discussion of the arguments relating to optimum coding theory so that only a simple system will be described in order to provide a sense of the process. Coding and decoding for transmission of a signal on a noisy channel are respectively the steps taken between the information source and the transmitter and between the decision maker and the recipient. The simplest decision assumes that two wave forms have been selected to use in signaling and that during each use the receiver knows that one of the two is sent. The receiver must decide, on receiving the noisy waveform, which is more likely. Decisions will occasionally be incorrect and the binary digits from the decision device will occasionally differ from those entering the transmitter. Figure B-30 is the customary schematic of a binary symmetric channel which includes modulator, transmitter, transmitting antenna, medium, receiving antenna, receiver and decision-maker. This channel accepts binary input digits and produces binary output digits. P_c is the probability of an error and $q = 1 - P_c$ is the probability of correct transmission. Figure B-31 shows a system where the fixed channel is preceded by a coder and followed by a decoder which produces another binary channel with a slower signaling rate and a smaller crossover probability.

The digits entering the coder are divided into blocks of M digits. Additional check digits are produced, each of which is a different function of the M message digits, bringing the total number in the block to N. The decoder examines each of the check digits to correct errors made in the decision maker. Two results are immediately apparent: a delay is introduced, equal to the block size N, and the transmission rate, $R = M/N$, is reduced.

The decision maker is allowed a little more probability information than that of binary decision. If the signal is close to the expected values of 0 or 1, the receiver prints a zero or one; otherwise the receiver prints an x, indicating erasure of the digit by the channel.

Figure B-32 is an example of a block parity-checking code. The 5 digit message generates 6 check digits by forming the scalar product of I_k and each row of the coding matrix $[A_{jk}]$. Each of these scalar products mod 2 is a check-digit. The six check digits are added to the 5 digits, I_k, to give an eleven digit message of which, in transmission, there appear three erasures. At the decoder the first five digits generate six check digits which are compared with the last received six digits. In this case the result is an error-free message. The code is completely specified by the matrix $[A_{jk}]$ which is used at transmitter and receiver. The formation of the check digits can be implemented by conventional digital circuit techniques.

This example demonstrates one method of coding which, for suitably low signal-to-noise ratios, detects and corrects errors. More general forms of coding change the elements of the message into more complex elements which make it possible to detect a mistake in an element.

Feed back systems involve a two way link which can be used for error control in a variety of ways. For example, in the error detection method described above, a detected error would be followed by a return link request for retransmission. Other feedback methods describe the present characteristics of the channel to allow for appropriate coding or interpretation of the message under the measured channel conditions. Combinations of coding and feedback range from the simple form of periodic message repeating for verification to sophisticated error-correction codes which can cope in a predictable fashion with a given form of interference.

Message
digits

$I k = 00101$

Coding
Matrix - $\begin{bmatrix}A_{jk}\end{bmatrix}$ $\left.\begin{bmatrix}01001\\10111\\00101\\11010\\01101\\10010\end{bmatrix}\begin{matrix}1\\0\\0\\0\\0\\0\end{matrix}\right\}$ Check digits $C_j = \sum_{4=1}^{5} A_{jk} I k, \; 1 \le j \le 6$

Coded message = 00101100000

Received message = 00XX110X000

Decoding equations

Initial form	Unknowns isolated	Solution
$0 + 0 + 0 + 0 + 1 = 1$		
$0 + 0 + I_3 + I_4 + 1 = 0$	$I_3 + I_4 = 1$	$I_3 = 1$
$0 + 0 + I_3 + 0 + 1 = X$	$I_3 = 1 + X$	$I_4 = 0$
$0 + 0 + 0 + I_4 + 0 = 0$	$I_4 = 0$	
$0 + 0 + I_3 + 0 + 1 = 0$	$I_3 = 1$	
$0 + 0 + 0 + I_4 + 0 = 0$	$I_4 = 0$	

Decoding erasures by parity-check equations.

Figure B-32 Block Parity-Checking Code

This is a general approach to the transmission of information with rates of error which can be controlled. It should be pointed out that the considerations discussed here apply not only to auxiliary information transmission but also to fundamental elements of the surveillance system; i.e., coded track circuits.

A digital system used to transmit vehicle control commands might send a 28 bit word which contains a 5 bit Bose-Chaudhuri coded security group. This particular code can detect up to 5-consecutive-bit errors. For a modem with 10 dB signal-to-noise ratio (false detection probability of 5×10^{-4}) the system has an error probability of 8×10^{-11} and for a 1200 bit per second transmitting rate, an error in one word per nine years is expected.

From the foregoing it can be seen that in communication systems that have an inadequate signal-to-noise ratio, error rates can be kept arbitrarily low by suitable coding to fit the system error requirements providing delays can be tolerated. While this is a valid comment and is a most useful concept in systems where power is limited and the spectrum is specified, it is also true, that for train communications, signal-to-interference ratios may be kept suitably high by removal to a suitable spectral region and the use of adequate signal power so that analog systems similar to that described in a previous section can be quite satisfactorily employed. An analog system is here defined as one in which a continuously variable modulation parameter of the communication carrier corresponds to a continuous value of a train system parameter. Future component development progress will decide which of the systems will be most economical, least complex and most reliable.

B9. FAIL-SAFE COMMUNICATIONS

Train surveillance systems and track circuits both have fail-safe as their standard of safety. This means that in case of failure of any part or parts of the surveillance systems the resultant mode of operation will not be unsafe. To be more specific, consider an insulated track circuit shown in Figure B-33. Fail-safe operation assumes many things including a vital relay which never sticks in the energized position, no accidental conductive paths between the Power Supply II and the green signal lamp, no failures of the track circuit Power Supply I which might energize the track at a level such that a train does not de-energize the relay, no failure of track circuit insulators so that an adjoining block power supply would be able to keep the green lamp lit, and no track debris which insulates rails so that a train cannot shunt a block relay.

Under circumstances that provide for traffic regularity, regular inspection and refitting of relays, and rail cleaning, the unsafe failure of this simple system has a very low probability, but is possible. The system can be made less susceptible to unsafe failure by adding redundant features. These will, however, raise its safe failure rate making it less reliable. The important point is that the concept of fail-safe operation can be considered an element of a more general reliability concept in which the probability of single component unsafe failure is very low. Systems other than the simple one of Figure B-33 can be considered and the notions of single and multiple component failure, redundancy, reliability, performance degradation as a response to component failure, and other trade-offs in performance and safety can be applied.

Safety is not an absolute quantity which can remain uncompromised for a range of system variations. Safety parameters can be defined which may be a continuous function of the system state or which can be quantized such that a defined quantity of change in the state is required to change the value of the safety parameter. The safety parameter must be adequate, but overspecifica-

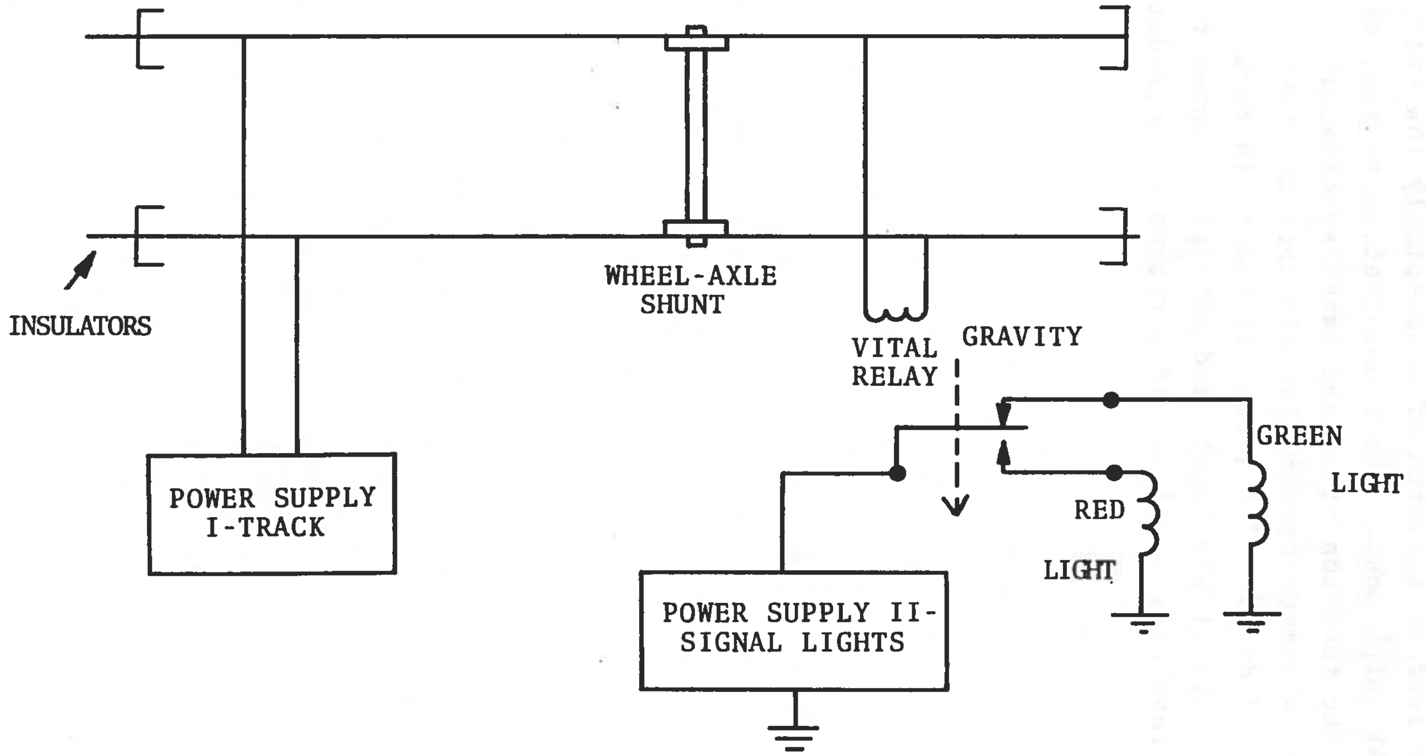


Figure B-33 Fail-Safe Insulated Track Circuit tion may lead to a system of unacceptably low reliability and unacceptably high cost. The communication system, since it must perform the function of surveillance specifically as well as indirectly by communication channels such as voice - radio and transfer of digital data, must be judged in terms of the frequency of occurrence of its single and multiple component failure modes and the resulting magnitude of performance degradation.

SUMMARY

The surveillance and communications systems, because of their vital role in train safety, must be given high priority in examining overall train safety. Track circuits appear to have an excellent record for safe operation and yet seem to be severely limited in their dependence on ballast conditions, weather, and train-rail interaction. Ballast leakage and track self inductance set high frequency limits of operation and therefore there is no place in the acceptable operating spectrum where propulsion current interference can be avoided.

Inductive two way signaling appears to have great potential for providing high data rates, operation in an interference free spectral range and multi-purpose control links. However, there is not, as yet, a long history of successful operation and actual statistics for track circuits operation are not available.

A unified communications engineering approach to information transmission is necessary so that optimum coding and feedback (message verification) are properly employed. All commands should be verified at the command origin.

The concept of fail-safe design is not by itself an adequate guide to the design of a complex system and it should be incorporated into a broader concept involving hierarchical safety levels.

Only systems for which the technology seems quite available have been discussed in this Appendix. Developments such as microwave radar systems which permit collision avoidance have not been discussed because the technology is not sufficiently advanced. In order that hardware with the requisite safety data be available, development programs for such equipment as well as exhaustive testing programs are necessary. These programs could also be applied to many presently used components. The literature regarding the safety and reliability of such components is not available at this time or is inadequate for rail rapid transit design requirements.

A few other subjects requiring careful study in future programs are

1. Track-wheel contact resistance
2. Natural ballast resistance studies
3. Ballast design study
4. Effect of weather on inductive, conductive and radiative coupling equipment
5. Insulation of track from ballast
6. Interference environment for trackside communications

APPENDIX B BIBLIOGRAPHY

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APPENDIX C

AUTOMATIC TRAIN CONTROL SYSTEM SAFETY CRITERIA, AVAILABILITY, AND RELIABILITY

Current automatic train control system design criteria for rail rapid transit systems are based on the "fail-safe" concept. Fail-safe is defined as a characteristic of a system which ensures that any malfunction affecting safety will cause the system to revert to a state that is generally known to be safe.(1) This design criteria when used to implement an automatic train control system, usually results in fail-safe circuits based on closed loop principles. This means that the system is designed such that broken wires, damaged or dirty contacts, a relay failing to respond when energized, or a loss of power supply energy does not result in conditions generally known to be unsafe. Components or subsystems which do not have such self-detecting characteristics are generally used only when their failure cannot cause unsafe conditions, even if added to other failures.

To ensure that a failure is fail-safe, automatic train control systems have historically been designed such that these self-detecting component or subsystem failures in car-borne equipment cause the involved train to stop. If the failure occurs in wayside equipment, the design criteria has historically dictated that all trains in the involved section of track be stopped. Once stopped, the operational procedure generally involves changing out of the automatic train control mode into a manual mode such that the affected train(s) can proceed to operate at a safe, more restricted speed than that normally permitted with no failure.

Unfortunately, when such a failure occurs in a rail rapid transit system's automatic train control system and stops an individual train or all trains at a particular section of track, the failure generally causes all trains on that particular line to at least be delayed and perhaps to be stopped until the failure is repaired or the train is removed from service. This is because the mean time between repair of such failures is generally large compared to the average headway between trains and because removal of the failed train from service occurs at relatively slow speeds.

In addition to being a significant operational detriment to the transit system, it can also be argued that stopping the train, operating it in other than an automatic train control fail-safe automatic mode (such as manually), moving it through various interlocks to remove it from revenue service, or causing other trains to move through interlocks in single track operation around the disabled vehicle creates additional risk. While it may be fail-safe, it may not be anywhere near as safe in an overall system sense as normal operations.

If such failures occur approximately weekly, and the procedures for handling the situations can be standardized in an overall system safety sense, then the fail-safe concept is sufficient as a primary system safety criteria. The system can also attain a high level of operational availability for revenue passenger service. If fail-safe failures in the automatic train control system occur more frequently, such as approximately daily, then the operational availability will decrease proportionately but the overall system safety level will tend to be about the same because the standardized procedures are still the same.

When fail-safe failures in the automatic train control system occur very frequently (more than once every day for example), occur concurrently at different places in the system, or occur sequentially within a short period of time at the same place in the system, then the safe set of analyzed procedures for system operation begins to be completely incompatible with the strategies needed to keep the system running. Under these circumstances, especially when continued for extended periods of time, the pressures to obtain reasonable operational availability of revenue passenger service may significantly increase safety risks and invalidate the fail-safe concept.

There will always be some point where the possible combinations and permutations of multiple failure sequences become impossible to analyze and commit to procedures in an overall system safety sense. Therefore, it is extremely important that the automatic train control system equipment be designed and demonstrated to achieve a reliability level commensurate with experiencing less than approximately one fail-safe failure every few days. This, in turn, implies a reliability budget and a set of priorities for all automatic train control hardware and software subsystems and their elements at least down to the equivalent of the printed circuit board level. It also implies the need for measuring reliability performance, diagnosing failures, and documenting maintenance actions, especially during the early testing of subsystems, initial system level checkout phase, and throughout the lifetime of the system.

In the past few paragraphs terms describing the relative frequency of failures such as "every several days," "every few days," and "frequently" have been used for example purposes. The actual numbers in such an argument would depend on the particular system design and be based on quantitative information regarding historical safety statistics, currently insufficient for the derivation of meaningful numbers.

There is generally one automatic control system per train and its failure can stop the whole train. In contrast, there are many types of individual component or subsystem failures that might stop a car or a married pair of cars but which can otherwise be tolerated and compensated for when the disabled car is just one redundant element of a train. From an overall operational availability point of view this implies that the reliability of the automatic train control system must be just that much higher than that of the propulsion, braking, door, and other subsystems of an individual car.

In view of all these considerations and in light of actual performance of existing systems, it is concluded that the fail-safe concept by itself is an inadequate automatic train control system design criterion for ensuring high levels of overall system safety and operational availability. Wherever possible in all new rail rapid transit systems, a new design criteria should be adopted which requires the following:

1. Any first failure within any subsystem of the automatic train control system should be fail operational (and still fail-safe). This means that such a first failure would allow the complete transit system to continue to operate at full capacity without degrading safety.
2. When operating after a first failure in a subsystem, any single additional subsystem failure should be fail-safe, i.e., shall not result in unsafe conditions.
3. Fail-operational first-failures may occur in other subsystems anywhere in the total transit system either simultaneously or sequentially so long as these subsystems are independent.
4. There cannot be any combination of otherwise allowable first failures within a group of subsystems which will result in an unsafe condition for the transit system as a whole.
5. The detailed procedures used to operate trains, as well as the overall system, following a fail-safe failure and prior to repair of the failure, removal of the train(s) from revenue service, or restoration of normal service, should be ones previously analyzed and approved by the appropriate regulatory safety agency as part of the overall transit system safety program.
6. First and second subsystem failures should be self-detecting or readily detectable, down to the equivalent of the subsystem and circuit board levels, with a minimum of automated test equipment. Careful records of all past automatic train control system failures, diagnoses, repair, and failure analysis actions should form the basis for determining the level of testing and the level of system integrity required for redispatch at a terminal turnaround.

7. Overall system design and subsequent, regularly scheduled operational verification of automatic train control system equipment and procedures should ensure that the automatic train control system (including car-borne equipment) can initially and continuously meet the system fault tolerance requirements previously stated. Passenger safety requires that the degree of failure protection must be periodically tested and verified. Ideally, this should be done after very short time intervals in the early stages of system start up and less frequently as procedures stabilize and reliability problems are solved.

8. Since the automatic train control system is only one element of the overall rail rapid transit system, its safety program should form an integrated element within an overall safety program for the entire transit system. The interfaces and inter-operational procedures between the automatic train control system and other elements of the transit system to achieve adequate safety levels must be as carefully defined, mechanized, and verified as those between automatic train control subsystems.

High levels of automatic train control system reliability generally imply subsystem simplicity and require attention in the design to high quality components for equipment reliability, check redundancy, and separation of individual functions to further simplicity, ease failure diagnosis, and hasten repair. In addition the design must consider the proper use of multiple channel redundancy, self-checking features, and periodic preventive maintenance in order to achieve fail-safe, graceful degradation of operational capability of the overall transit system in the event of single and multiple failures.

The human operator, performing in the check redundancy role defined in Section 5.2.3, can perform numerous failure detection and failure diagnosis functions and thus contribute to implementation of the fail-operational first failure concept and the minimization of the mean time between repairs. The operator can also provide the judgmental factor for changing to and implementing a variety of back-up operational modes in the graceful degradation process based on particular types of failures. To perform these functions properly, and as an integral part of the overall system, he must be given the necessary information and must interact with the system through adequate display and communication devices.

For system designs which are based on the use of simple, demonstrated subsystems and components, and for those components which are impractical to make redundant, consideration may be given to waiving the required fail-operational fault tolerance level and to require only that the system degrade to a state generally known to be safe after a single failure. A typical example is the vital relay widely used in rail rapid transit systems. This is a very reliable relay used in systems designed to stop vehicles for any type of failure in the relay or overall system. The relay failure mode which could cause an unsafe condition is a failure to open. Detailed relay design, the use of gravity for an opening force and a regular maintenance have been employed to attempt to eliminate a "failure to open" as a failure mode.

Where fail-safe design is used, it must be limited to applications where the fail-safe characteristics of every element can

1. Be demonstrated by a test program, or
2. Be based on extensive known operating history of the selected components and system.

In addition, where fail-safe approaches are used, a complete analysis should be performed to assure that there are no failure modes that could cause an unsafe condition. This analysis should include overall system design, individual circuit designs, component failure modes, undetected wiring errors and potential wiring failures (shorts and opens). As a part of this requirement, a failure modes and effects analysis for multiple failures is required. This analysis should be carried to the level of detail necessary to demonstrate compliance with the requirement.

In a similar vein, efforts should be made to test and evaluate the reliability of continuously self-testing devices which are in common use in many European systems and advertized to be fail-safe, but which cannot meet Federal Railroad Administration standards as currently interpreted. These devices promise significant cost, weight, and design flexibility advantages if allowed to be used in United States rail rapid transit systems.

APPENDIX D

APPLICATIONS OF HIERARCHICAL CONTROL CONCEPTS TO AUTOMATIC TRAIN CONTROL

NOTE

THIS APPENDIX IS A REPORT WRITTEN BY R.E. GOODSON, WHILE A CONSULTANT TO THE U.S. DEPARTMENT OF TRANSPORTATION, TRANSPORTATION SYSTEMS CENTER, AND COVERS A STUDY MADE IN SUPPORT OF THE OVERALL EFFORT.

D1. INTRODUCTION

In this analysis of some functions of the control system for a mass transit rail system, the emphasis is on function and operational design, particularly hierarchical control concepts, rather than hardware. Some of the decisions which must be made concerning hardware realization and location of functional concepts are highlighted. Safety is discussed both as an independent goal and as it relates to operational functions. Reliability considerations are discussed only briefly although the interaction between reliability and safety are important.

The basis for this report is the examination of several mass transit systems such as BART in San Francisco, WMATA in Washington, MBTA in Boston, the Sao Paulo system, and other systems using varying degrees of automatic train control. In addition, experience in functional analysis of similar systems, particularly in the process industries, governed the study and the methods of description. Finally, the study is limited to a functional description of mass transit rail systems under state-of-the-art implementation. Analysis of alternative realizations has received little attention. The application of hierarchical control concepts was the main goal. An analysis by simulation of alternatively configured systems should be a goal of the future work in this area with special emphasis on the interacting decisions regarding function assignment, reliability, safety, and operational flexibility. One of the main decisions affecting the system is the mix between manual and automatic operation of the system. This decision is important for many different reasons. The investigation of this mix, given all the real system constraints, may direct other than a fully automatic system.

D2. TRANSIT TRACK SYSTEM

It is assumed that the transit system is made up of dual track segments with crossovers and storage areas. Nodal points in the system area are those switching points where trains converge or diverge to and from more than two track segments.

Terminal points are locations where a track ends and trains must be routed to the track going in the opposite direction or else stored. A yard is the place where trains are maintained, made-up, tested, dispatched and received from operation. A storage area is a location and track where a train can be shunted off the main tracks. A vehicle is the single car of which trains are made up. A train is the assemblage of vehicles to make a passenger carrying unit. Revenue operation is regular passenger operation of a train. A crossover is a track segment connecting the dual tracks. An X-crossover is a dual net of intersecting crossovers. A station is a point of passenger entry and exit to the trains. A switch is a point in the track where a train can be shunted to one of two directions. A block is a given length of track which is separated from adjacent blocks for train operation by signaling or other communication means. A track system is a topological layout of dual sets of tracks with nodal, terminal, switch, crossover, yard, storage, and station points identified.

D3. BASIC FUNCTIONS

Given a track system as outlined above, the operation of a mass transit system falls under the general functions of:

1. Traffic Supervision
2. Train Operation
3. Train Protection

These functions are interrelated but each may be addressed separately for the basic analysis. The train supervision function has to do with overall scheduling and routing, number of trains in operation, emergency and contingency procedures, train make-up, and system maintainance. Train operation is the function of moving unit trains along the system at the correct speeds, headways, and with appropriate stops and passenger management at the stations. Train protection has the primary function of safety of passengers, system personnel and equipment. The functions here are to assure train separation, provide interlocking switches in safe operational configurations, provide malfunction protection, and define procedures in emergency or anomalous situations. These functions are listed in more detail in Table D-1.

D4. TRAIN PROTECTION

Train protection will be discussed first since this concept is central to many operational practices and influences total system design. The basic train protection concept is the block system of segmenting track. Lengths of track as short as a few hundred feet and as long as several miles, depending on the type of rail system, are designated as blocks with equipment to identify a train's entry into the block, presence in the block, and/or exit from the block. The safety function manifests itself in some operational procedure based on the rules that a train approaching an occupied block must reduce speed and a train must not enter an occupied block.

In addition to separation assurance accomplished by some type of block system and logic, it is mandatory to provide safe switching logic at each switch location within the track system. Positive switch locking, logic to insure safe switching and reliable switch position sensing hardware are required for train protection.

A third area of train protection is overspeed protection. For segments of certain track systems under adverse conditions due to weather, traffic, or malfunction, the maximum speed of the train should be limited. In addition, under normal operation, there is a given speed at any time which should not be exceeded. The overspeed protection system must supply the information to the train and also the hardware to assure that the train is operating within its commanded speed.

Train protection means passenger safety in loading, transporting, and unloading passengers, and requires that the doors open at the stations and only at the stations, that doors close without harming passengers, and that the train does not injure any persons while in operation. There are numerous concepts and

TABLE D-1 FUNCTIONS FOR AUTOMATIC TRAIN CONTROL

- 1.0 TRAFFIC SUPERVISION
  - 1.1 Mode Control
    - 1.1.1 Scheduled (fixed)
    - 1.1.2 Demand-responsive
    - 1.1.3 Manual
    - 1.1.4 Automatic
    - 1.1.5 Hybrid
    - 1.1.6 Emergency
  - 1.2 Scheduling, Routing
    - 1.2.1 Nominal
    - 1.2.2 Contingency
    - 1.2.3 Switching
    - 1.2.4 Interlocking
  - 1.3 Yard Dispatching
    - 1.3.1 Start-up
    - 1.3.2 Shut-down
    - 1.3.3 Transient
  - 1.4 Vehicle Management
    - 1.4.1 Train assembly and disassembly
    - 1.4.2 Hostlering
    - 1.4.3 Pre-dispatch testing
  - 1.5 Automatic Scheduling of Maintenance
    - 1.5.1 Vehicles
    - 1.5.2 Network

TABLE D-1 FUNCTIONS FOR AUTOMATIC TRAIN CONTROL - CONTINUED

        - 1.5.3 Wayside
        - 1.5.4 Station
        - 1.5.5 Local
    - 1.6 Train/Vehicle Identification

- 2.0 UNIT TRAIN OPERATION
    - 2.1 Velocity Profile Command
    - 2.2 Velocity Profile Control
    - 2.3 Vehicle Door Control
    - 2.4 Local Separation Assurance
    - 2.5 Emergency Intervention
    - 2.6 Passenger Management

- 3.0 TRAIN PROTECTION (SAFETY ASSURANCE)
    - 3.1 Train Location and Velocity
    - 3.2 Separation Assurance
    - 3.3 Route Interlocking
    - 3.4 Hazard Protection
    - 3.5 Overspeed Protection
    - 3.6 Malfunction Protection
    - 3.7 Passenger Safety
        - 3.7.1 Jerk Limits
        - 3.7.2 Deceleration and Acceleration Limits
        - 3.7.3 Door Interlocks
        - 3.7.4 Platform Door Sequence Control
    - 3.8 Operational Verification
        - 3.8.1 Monitoring
        - 3.8.2 Transmission

TABLE D-1 FUNCTIONS FOR AUTOMATIC TRAIN CONTROL - CONTINUED

4.0 MONITORING AND TRANSMISSION FOR CONTROL
  - 4.1 Vehicle Control
  - 4.2 Wayside Control
  - 4.3 Station Control
  - 4.4 Central Control

5.0 COMMUNICATIONS
  - 5.1 Vehicle-to-wayside/wayside-to-vehicle
  - 5.2 Wayside-to-station/station-to-wayside
  - 5.3 Station-to-central/central-to-station
  - 5.4 Vehicle-wayside-vehicle
  - 5.5 Station-to-station
  - 5.6 Emergency to Central

functions of train protection which must go into the design of the track system, stations, and controls. The discussion here centers around the design and operation of the automatic control system as it relates to train protection.

D5. TRAIN DETECTION SUBSYSTEM

The train detection subsystem is the basic concept for train protection and operation. The function of this subsystem is to provide positive information on the location and, in some cases, velocity of trains within the system, at all times. This information is vital for both train protection and operation. Many alternative realizations of this function are possible, for example, continuous measurement of position using a voltage divider technique with either one of the tracks or a separate conductor serving as the sensing line. Radar techniques have been proposed. Different schemes of wayside sensing have been used. However, the vast majority of present and proposed mass transit rail systems use the block occupancy system or variations of the block system. The common characteristic of all the train detection subsystems, however, is a fail-safe design and operation philosophy. Any single failure of any component of the system should result in a state generally known to be safe.

The block system subdivides all the track into discrete segments called blocks. The presence of a train or a portion of a train is sensed in each block. The simplest systems activate visual signals in the adjacent blocks. The signals are the common red, amber, and green lights. The operational philosophy to assure that two trains maintain greater than a certain minimum distance apart can be quite complex but involves switching the lights in some combination to give information to the operator. This system is entirely local and modular. The basic sensing means is a track circuit using the rails as signal carriers and the trains as shorting means. Relays are held closed by current passing through the track with a power supply at the other end of the block. The absence of current allows gravity to drop the relay speed control loop. In addition, for a power failure, enough energy should be stored to provide a full stop under worst case conditions with maximum braking.

Another primary question is the level of manual control designed into the train speed control system. It is possible to have a fully controlled system with a manual implementation of speed commands. This would save considerably on vehicle control hardware costs. The operator would implement commanded speeds as signaled in the cabin. An overspeed protection system would still be included in the vehicle design which would both provide alarm and cut power (or apply brakes). A fully automatic system could have a manual button which would allow full control from cabin displays. This is obviously the most costly in terms of primary loop hardware. However, some measure of manual control could provide a redundancy which would lower the cost of a fully automatic system without any manual control. In any case, it is important to provide a graceful entry of the operator into the loop if he can enter at all. The general concept of graceful system degradation where certain failures, e.g., loss of one of several drive motors, do not completely disable the system, is essential for reliable operation of the train system independent of the level of manual control.

D7. THE SWITCHING AND INTERLOCK SYSTEM

Once a route for a train is set and is interlocked with the routes of other trains, the switching logic is functionally set. Assuming that the switching and interlocking is automatically implemented, the only change in the switching logic would come under emergency conditions or on-line operational changes due to malfunctions or schedule revisions. The control for implementation of the switching and interlocking should be accomplished at the local level and should be commanded from the state of the system rather than from a time base. This means that switching should occur when the appropriate train is near a switching block and be triggered by the train itself. Thus, the train presence triggers the switching. This presence could be sensed at stations or by wayside sensors near the switch point.

Obviously, this critical function should have interlocking to prevent a series of switches to be set up incorrectly. Further switch positions could be signaled to the operator and to a central system. Also, the switching logic must be able to decide priority and change speed commands when unit trains approach a node simultaneously.

The main problems in switching occur for a system malfunction, during track maintenance, and at track nodes. A malfunction in the switching hardware or logic control requires independent manual or automatic verification of the switch position and locking and probably operational degradation. Also, returning a malfunctioning train in revenue service to a yard for maintenance or removing it from service requires special switching conditions. Finally, at track node points where trains are blending to one line or diverging to two lines, the switching logic must be able to safely adapt the operation of the system to satisfy conflicting demands. All of the switching logic relies on a reliable train detection system.

D8. HIERARCHICAL CONTROL CONCEPTS

The train control system should be viewed as a hierarchical control system with special emphasis on fail-safe and reliable operation. The process industries have had significant experience in applying computer control to complex systems and, in general, the following conclusions based on this experience are germane to train control.

1. Central computer control of a complex process distribute over a significant area (such as a steel or chemical plant) although initially considered desirable (1960-1968) has given way to the concept of small local control stations performing real-time functions and

communicating with a central facility at a low data rate. The main reasons for this concept are (a) wiring costs, (b) reliability of the central computer, (c) training of maintenance and operator personnel, (d) low cost and reliability of small, dedicated computers, (e) software generation costs, and (f) added reliability of hierachical control.

2. Movement away from local analog controllers to local digital controllers.
3. The central control facility is charged with the functions of: (a) system monitoring for alarms, (b) safety control procedures, (c) optimization of the total process, and (d) management information generation.
4. The operator-process interface needs special consideration since experience has shown that a significant (10% - 40%) portion of the time, some portion of the process is under manual control. This requires that the transition from manual to automatic and automatic to manual control should proceed smoothly with minimal process operational degradation.
5. The process operator's console should be designed with close attention to problems of human engineering, data rates, and total information content required to be absorbed by operators.
6. Maintenance requirements of process and control systems incorporating computer control increase compared to those requirements for systems without computer control.
7. Component failures in the process should be alarmed and operational procedures defined for these failures such that the control system may operate under limited process capability, i.e., graceful degradation should be a design goal.

8. Cascade control, where process commands are sent to a local control system and process measurements are used in an outer feedback loop to set these commands, have major operational advantages. For example, although velocity commands are given locally to trains, the posi tion versus time of the trains may be the main desired control command (a schedule). In such a case, central control may modify velocity commands to vary the relative positions of trains to better meet the schedule. A hierarchical control system embodying the above concepts is shown in Figures D-4 and D-5.

D8.1 Automatic Train Control - A Modular, Hierarchical System

An automatic train control system with the features discussed above and providing three layers of safety assurance and operational flexibility is outlined below. The basic control system is a set of local controls detecting location of trains, signaling speed commands, and modifying these commands as a function of the track occupancy and switch status ahead. This is the first level. It is designed using a fail-safe philosophy and is basically a separate independent system for complete train detection and speed commanding. Trains on the system are detected and receive speed command signals. This local first level system doe not necessarily monitor train velocity or apply the conservation and continuity laws of Section D5 above.

The second level of control applies the conservation and continuity laws of Section D5 above. This level is a safety back up which provides information to the next highest level and performs safety monitoring to the lowest level. Its function is to detect false occupancy signals and signal the next highest level, and to detect failures to identify a train and signal the lowest level and the next highest. The data received are:

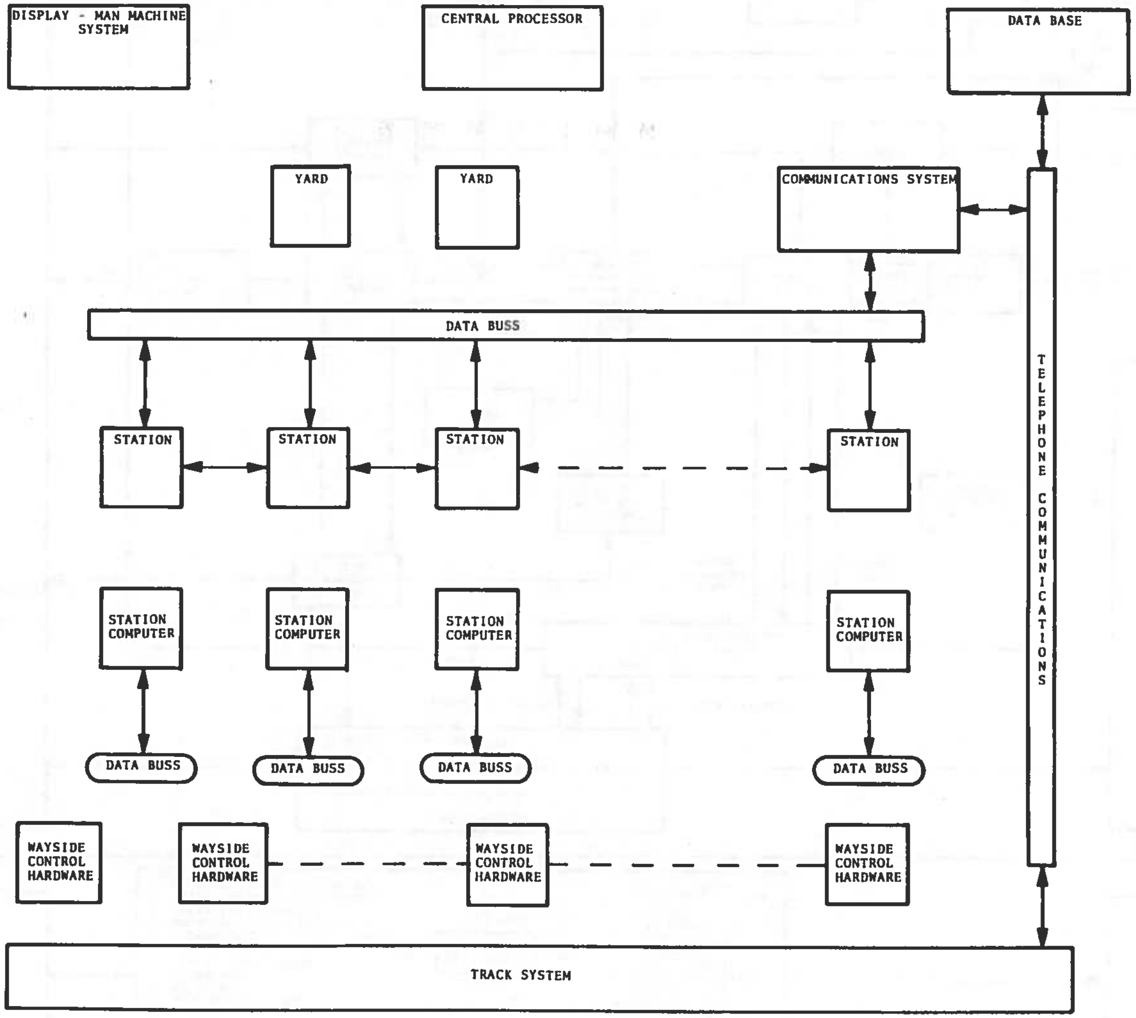
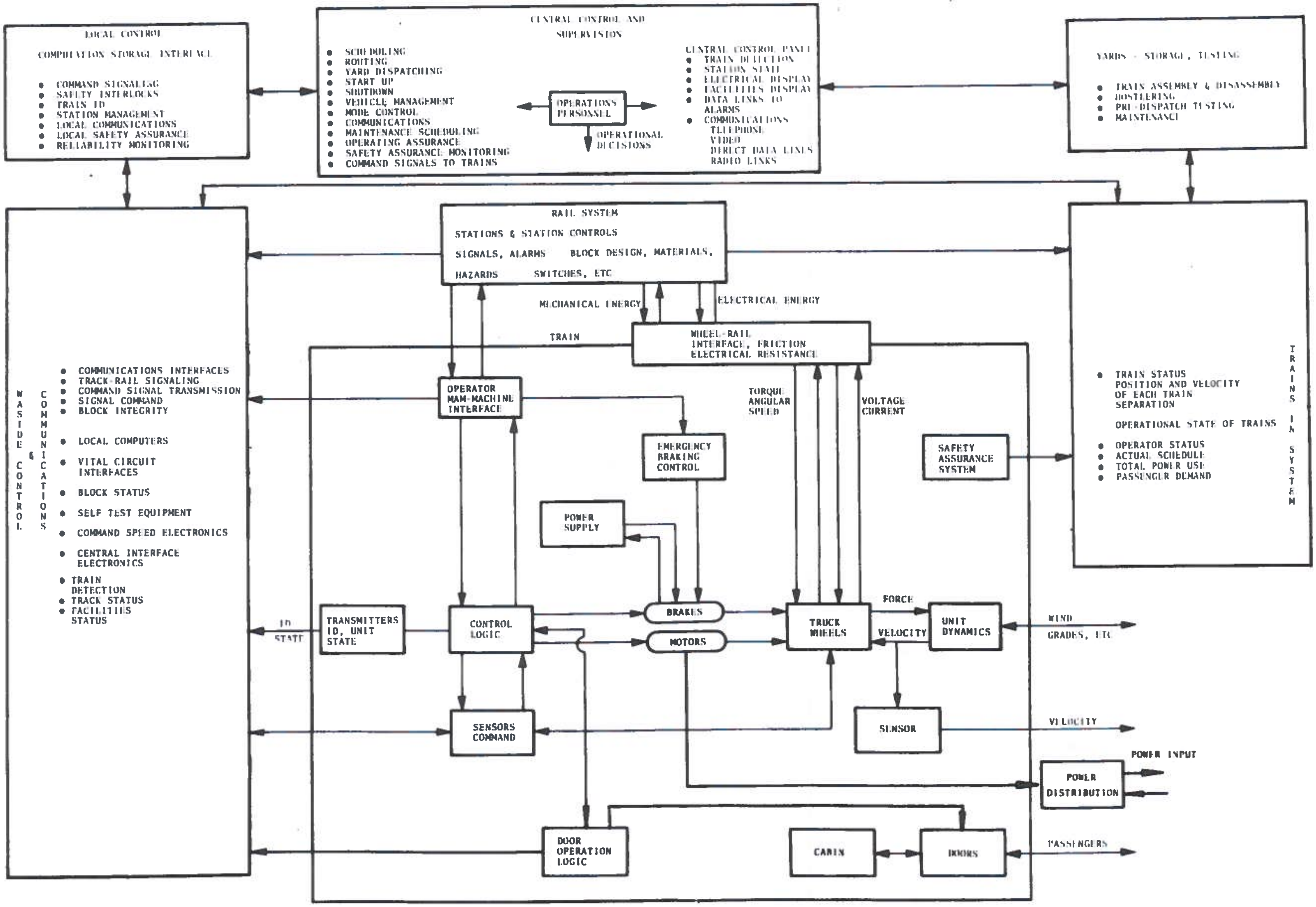


Figure D-4 Hierarchical Control System


LOCAL CONTROL
COMPILATION STORAGE INTERFACE
● COMMAND SIGNALING
● SAFETY INTERLOCKS
● TRAINS ID
● STATION MANAGEMENT
● LOCAL COMMUNICATIONS
● LOCAL SAFETY ASSURANCE
● RELIABILITY MONITORING
CENTRAL CONTROL AND SUPERVISION
● SCHEDULING
● ROUTING
● YARD DISPATCHING
● START UP
● SHUTDOWN
● VEHICLE MANAGEMENT
● MODE CONTROL
● COMMUNICATIONS
● MAINTENANCE SCHEDULING
● OPERATING ASSURANCE
● SAFETY ASSURANCE MONITORING
● COMMAND SIGNALS TO TRAINS
OPERATIONS PERSONNEL
OPERATIONAL DECISIONS
CENTRAL CONTROL PANEL
● TRAIN DETECTION
● STATION STATE
● ELECTRICAL DISPLAY
● FACILITIES DISPLAY
● DATA LINKS TO ALARMS
● COMMUNICATIONS
TELEPHONE
VIDEO
DIRECT DATA LINES
RADIO LINKS
YARDS - STORAGE, TESTING
● TRAIN ASSEMBLY & DISASSEMBLY
● HOSTLERING
● PRE-DISPATCH TESTING
● MAINTENANCE
RAIL SYSTEM
STATIONS & STATION CONTROLS
SIGNALS, ALARMS
BLOCK DESIGN, MATERIALS,
HAZARDS
SWITCHES, ETC
MECHANICAL ENERGY
ELECTRICAL ENERGY
TRAIN
WHEEL-RAIL INTERFACE, FRICTION ELECTRICAL RESISTANCE
WAYSIDE CONTROL & COMMUNICATIONS
● COMMUNICATIONS INTERFACES
● TRACK-RAIL SIGNALING
● COMMAND SIGNAL TRANSMISSION
● SIGNAL COMMAND
● BLOCK INTEGRITY
● LOCAL COMPUTERS
● VITAL CIRCUIT INTERFACES
● BLOCK STATUS
● SELF TEST EQUIPMENT
● COMMAND SPEED ELECTRONICS
● CENTRAL INTERFACE ELECTRONICS
● TRAIN DETECTION
● TRACK STATUS
● FACILITIES STATUS
OPERATOR MAN-MACHINE INTERFACE
EMERGENCY BRAKING CONTROL
POWER SUPPLY
TORQUE ANGULAR SPEED
VOLTAGE CURRENT
SAFETY ASSURANCE SYSTEM
TRAINS IN SYSTEM
● TRAIN STATUS
POSITION AND VELOCITY OF EACH TRAIN
SEPARATION
OPERATIONAL STATE OF TRAINS
● OPERATOR STATUS
● ACTUAL SCHEDULE
● TOTAL POWER USE
● PASSENGER DEMAND
ID STATE
TRANSMITTERS ID, UNIT STATE
CONTROL LOGIC
BRAKES
MOTORS
TRUCK WHEELS
FORCE
VELOCITY
UNIT DYNAMICS
WIND
GRADES, ETC
SENSORS COMMAND
SENSOR
VELOCITY
POWER INPUT
POWER DISTRIBUTION
DOOR OPERATION LOGIC
CABIN
DOORS
PASSENGERS

1. Block occupancy status
2. Train ID and velocity (not necessary)
3. Real time

The communications to the lower level are signals to trains in emergency situations and error detection signals to local station controllers.

The third level is central control. This level involves a central data base, computer, display, and operators. This level receives complete train detection data and the status of all auxiliary systems. Its function is to monitor the basic system for both safety and operational assurance. Central must operate within the safety concepts of the total system but it may utilize a separate communications network to the trains for additional information (usually phone lines). Central checks on operations, makes decisions in emergencies, and reroutes or schedules trains within the framework of the local safety system. Central control also continuously monitors the lower level for failures. Some attributes of such a three level system are listed below.

D8.2 Attributes of the Hierarchical System for Automatic Train Control

Level 1

1. The train detection system is a continuous measurement of the presence of a train on the track. Binary information is generated by independent track circuits or other detection circuits for train location.
2. The train detection data is fed by a data bus to local stations which control contiguous blocks of track. switches, and speed commands to this segment.
3. The whole track system is divided into several such segments.
4. The commanded speed signals are fed to the trains by track wayside equipment. This data transmission is continuous and must be present otherwise trains stop.

5. Speed command signals are generated for the station are by the station equipment in a fail-safe manner modified by the train detection data on an occupied portion of track ahead.
6. Train stops at stations and door openings are interlocked here for safety.
7. Switch positions are controlled by this level and also safety interlocking.
8. This local or station equipment is modified by higher level control such as adjacent stations transferring trains from one station area to the next, and for non-normal operations. The basic train safety is built within these local modules. Train operation can be modified by a higher level control. The built-in safet procedures of this lowest level control cannot be overridden by higher level control without manual intervention and appropriate procedures.

Level 2

1. Data on train location is fed to a higher level data base where the laws on train conservation and continuit formulated above are applied to compute train velocitie and track the trains through the system.
2. Anomalous behavior of the trains is monitored at this higher level and train safety and operation is compared against a master incremental schedule to provide data for modification of performance.
3. Trains can be automatically or manually stopped by this level but the next level below cannot be overriden.
4. Data flow for this level is train detection data, time and possibly train ID and velocity.

Level 3

1. Central control facility with displays, data base, computer, master schedules, and emergency procedures.

2. Third independent safety assurance system--central knows location of all trains, train ID by tracking or direct transmission and knows headways at all times. With malfunction or failures in lower levels, control can move to a safe operational state through a completely independent communications system to the trains, always within the safety procedures of the system.
3. Only central control can signal manual control.
4. Central has a data base for all maintenance and malfunctions.
5. Operators with appropriately designed displays provide a readily adaptive facility for operational changes within the safety constraint of the system.

D8.3 On-Board Train Control

The control systems on the trains to implement the signals from the first, second, and third levels of control are obviously critical. The trains must "obey" the signals sent for control for both safety and operational assurance. The signals received by the trains are

1. Speed commands as sent and modified by local controls.
2. Signals sent by the second level indicating the local headway, for example, or that the train is detected.
3. Communications from central on an independent data path.

The train must operate within system safety procedures always. Its performance can only be changed in an "as safe or safer" manner by the third or second levels. The implementation of the commanded performance of the train allows much flexibility. A train with a minimal level of automation would have significant automation still. Such a manual train would have

1. Speed commands and actual speed signaled to operator by a properly designed display.

2. Actuator for applying power and braking by driver.
3. Independent overspeed protection circuity.
4. Independent emergency braking circuity.
5. Manual door control but interlocked with train speed so doors would not open with moving train and train would not move with open doors.
6. Independent communication line to central.

The only difference between the most manual and the fully automatic train control is that the train speed command or error is implemented manually in the first case and by an actuator in the second. The commanded speed is under automatic control, and the overspeed controls are non-manual. The design requirements for both systems are stringent and involve basic safety concepts but the possible required presence of an operator even in an automatic system merits strong consideration especially for manual speed control, control of doors, and station stopping.

The decision on manual versus automatic train control shoul be mainly an economic and human engineering one. The same level of safety could probably be maintained in either and the manual control is much more flexible for the same initial capital investment.

D9. CONCLUSIONS

1. Several subsystems for automatic train control are basi to system safety. The most important is the train detection subsystem. It is essential that this system be designed to function without error under widely varying operating conditions. Safe design concepts and rel ability are equally important. The switching logic, th speed commands and the train protection system depend ultimately on this subsystem.
2. A train control system in modular form with distributed hardware locally controlling train operation and safety

has major advantages compared to a single centralized control handling all functions.

3. A hierarchical philosophy is desirable where the operation of the local control systems are monitored and system calculation performed for safety and operational assurance. Three independent levels of control are recommended; they are (1) local station, (2) backup safety, and (3) central control.
4. Approximate train velocities can be measured independent of the equipment on the train by computing discrete velocities from the occupancy detection signals. These velocities could be compared with the commanded velocity data at central to verify train operation and safety.
5. The progression of the logic sequence generated by a train passing through blocks could be monitored to detect anomalous behavior of the train detection subsystem and to track trains through the track system.
6. An independent communication path between central and trains is strongly recommended. Phone lines are satisfactory for an operator in the cab.
7. The decision on the amount of manual versus fully-automatic control on the trains should depend on two factors. The first is a detailed analysis of the performance characteristics of manual speed implementation given a well-designed cabin display and control panel for the desired headways. Included in this is the training required and long-term availability of qualified personnel. The second factor is a detailed cost analysis of fully-automatic versus the degree of manual control considered. In any case, the incorporation of the man into the control system should be a design problem approached with special care.

8. There are strong reasons to have central control receive all track occupancy data block by block and to alarmed in case of anomalous system behavior. This r quires a well-designed central control facility.

APPENDIX 1

DATA RATE COMPUTATION FOR CENTRAL PROCESSOR BLOCK PROGRAM

1. Given a central computer receiving occupancy status from B blocks.
2. Given M trains each of length L ft.
3. Given average half time in block at maximum speed of T seconds (train entering and exiting counts as two signals per block).

Problem

Estimate data rates, storage requirements, and computational burden on central computer to: (a), calculate discrete velocities of all trains and use data to track trains; (b), calculate and alarm anomalous behavior of occupancy detection; (c) alarm deviations from commanded speeds.

Assumptions - First Method

1. Occupancy detection status changes are handled as interrupts on main computer with X bits per word sent to computer representing the status of a section of the track system.
2. Status interrupt bits are serial with close to highest priority.
3. Differential time of status change recorded locally and transmitted with status change.

Estimate

1. Average rate of interrupts/second = $\frac{M}{T}$
2. Bits required to monitor status = B
3. Number of interrupt lines = $\frac{B}{X}$
4. Words of storage for trains identification = M
5. Words of storage for train location = M

6. Words of storage for train velocity = M

7. Words of storage for train length = M

8. Words of storage for train desired velocity and limits (Not a simple problem - depends on software and hardware of computer. For 10 command speeds and subtle tabular block assignment, i.e., blocks 1-210 have max velocity, blocks 211-433 have the velocity just under maximum, etc. 10 + 20 branch words plus 20 limits would suffice) = 5 (number of speed commands) (modified commands), 3B.

9. Words of storage for times of status changes = 2M

10. Calculation time $\frac{M}{T}$ computations/sec. of velocity, velocity within limits and position.

1 Division)
Branches)
Limit checks)
Fetch)
Stores)

less than 10 ms/computation for 25% duty cycle required - may be stringent

Example 1

M = 100
B = 2000
X = 32
T = 5 secs.
Speed commands = 8
Modifications = 3

20 interrupts/second
123 16 bit words for status
62 interrupt lines
600 words for train status
120-6000 words for alarm
plus 1000 words for program

Assumption -

Second Method

1. Occupancy status entered synchronously by computer at a given r

2. Timing done in central processor.

3. Buffer provided at central so computation proceeds on interrupt basis.

Estimate

Numbers 2, 3, 4, 5, 6, 7, 8, 9 and 10 same as above

In addition,

11. Number of times per second all status bits are read = S

Example 2

Same data as example 1 except X not defined and S = 5

Data rate to central

5000 bits per second transmission rate

20 computations per second worst case

Same number of storage locations as in example 1

Conclusions

1. Computation rate requirements may be stringent.
2. Data rate in First Method very low.
3. Data rate in Second Method relatively high.
4. Hardware requirements locally greater for First Method including oscillator counter at each station.
5. Communication lines to central required in both cases for serial bit transmission.

APPENDIX 2

ERROR ANALYSIS FOR TRAIN VELOCITY ESTIMATE FROM BLOCK OCCUPANCY STATUS

1. $\dot{x} = v(t)$

2. $\dot{v} = a(v,n)$, given

3. S_n = block designation, $n = 1,2,\text{---},N$

4. t_x^m = time to cross given points on tracks of both front and back of train

5. Blocks of length ℓ_n, $n = 1,2,\text{---},N$

6. Trains of length L_m, $m = 1,2,\text{---},M$

7. Criterion - separation shall be less than T seconds

8. Separation distance is from head to head = S_m^ℓ, m = train number, ℓ = train number of following or preceding train, i.e., $\ell = m+1$ or $m-1$

9. assume $v_n = \left(v_n^o - v_{n-1}^o\right)\left(1-e^{-\frac{t_n}{T_n}}\right) + v_{n-1}^o$

   Then, $x_n = \left(v_n^o - v_{n-1}^o\right) t_n + v_{n-1}^o t_n + \left(v_n^o - v_{n-1}^o\right) T_n \left(1-e^{-\frac{t_n}{T_n}}\right)$

   $$x_n = v_n^o t_n + \left(v_n^o - v_{n-1}^o\right) T_n \left(1-e^{-\frac{t_n}{T_n}}\right)$$

10. As train goes through the track system, data t_k^m is obtained as a series of numbers as follows:

    t_1^m is when front of train m reaches block 1

    t_2^m is when rear of train m reaches block 1

    t_3^m is when front of train m reaches block 2

11. These correspond to lengths (assuming $L_m < \ell_n$)

    $X_1 = 0$
    $X_2 = L_m$

$$X_3 = \ell_1$$

$$X_4 = \ell_1 + L_m$$

$$X_5 = \ell_1 + \ell_2$$

$$X_6 = \ell_1 + \ell_2 + L_m$$

$$X_7 = \ell_1 + \ell_2 + \ell_3$$

12. For v_n^o, ℓ_n, L_m, known t_k^m results (must perform inversion to find t_k^m)

13. Compute velocities

$$\overline{v_2^1} = \frac{L_m}{t_2^m - t_1^m}$$

$$\overline{v_3^1} = \frac{\ell_1}{t_3^m - t_1^m}$$

$$\begin{matrix} | & | \\ | & | \\ | & | \end{matrix}$$

These velocities are averages, obviously over the lengths in 11 above. Also, they are subject to the errors in the time measurements. However, they are indicative of the true state of the trains and may be used to compare against commanded velocities.

14. Velocity computation error analysis for error analysis of the velocities measured in 13 above consider three cases.

a) Constant velocity, v_n^o, over a block

b) Constant acceleration, a_n^o, over a block

c) Exponential acceleration over a block

$$a_n = \pm\, a_n^o\, e^{-t/T_n}$$

In addition, define

$\overline{t}_s$ = mean sensing time for train detection (time delay from train entering block until switches have changed state)

$\bar{t}_r$ = mean transmission delay time - time to transmit switch state to velocity computation memory.

σ_s = standard deviation of $\bar{t}_s$

σ_r = standard deviation of $\bar{t}_r$

For all three cases, consider a train of length L_m entering a block of length ℓ_n and let the data be t_1^m, t_2^m, t_3^m, and t_4^m, corresponding to the times indicated in 10 above. The velocities are computed as follows.

a) For the constant velocity case, the actual train velocity is v_n^o. The computed velocity for the first data is:

$$\bar{v}_2^1 = \frac{L_m}{t_2^m + \bar{t}_s + \bar{t}_n + \varepsilon_2 - t_1^m - \bar{t}_s - \bar{t}_n - \varepsilon_1}$$

where ε_i are the errors due to the assumed mean values of $\bar{t}_s$ and $\bar{t}_r$. Note that these times cancel

For the subsequent data

$$\bar{v}_3^2 = \frac{\ell_n - L_m}{t_3^m - t_2^m + \varepsilon_3 - \varepsilon_2}$$

$$\bar{v}_4^3 = \frac{L_m}{t_4^m - t_3^m + \varepsilon_4 - \varepsilon_3}$$

Now the actual velocity may be used to calculate errors as follows

$$E_1 = v_n^o - \bar{v}_2^1$$

$$= L_m \left[\frac{1}{t_2^m - t_1^m} - \frac{1}{t_2^m - t_1^m + \varepsilon_2 - \varepsilon_1}\right]$$

Defining

$$\Delta t_1 = t_2^m - t_1^m$$

$$\Delta t_2 = t_3^m - t_2^m$$

$$\Delta t_3 = t_4^m - t_3^m$$

$$E_1 = v_n^o \left(1 - \frac{1}{1 + \frac{\varepsilon_2 - \varepsilon_1}{\Delta t_1}}\right)$$

$$E_2 = v_n^o \left(1 - \frac{1}{1 + \frac{\varepsilon_3 - \varepsilon_2}{\Delta t_2}}\right)$$

$$E_3 = v_n^o \left(1 - \frac{1}{1 + \frac{\varepsilon_4 - \varepsilon_3}{\Delta t_3}}\right)$$

For a 300' train traveling at 80 mph

$$\Delta t_i = \frac{60}{88} \frac{300}{80} = 2.55 \text{ secs.}$$

Assume $\bar{t}_s \sim 0.5$ seconds with standard deviation of 0.15 seconds and $\bar{t}_r \sim 0.5$ seconds with σ_r of .1 second. The standard deviation of the error is then

$$\sigma_{E_1} \sim \frac{\sqrt{2}}{\Delta t_1} V_n^o \sqrt{\sigma_s^2 + \sigma_r^2}$$

$$\sigma_{E_1} \sim 8 \text{ mph}$$

or ~ 10%

If the block were shorter than 600 feet, the next velocity computation would involve a larger standard deviation.

For a block of 500', the standard deviation relative to Δt_2 would be

$$\sigma_{E_2} \sim \frac{\sqrt{2} \quad V_n^o}{\Delta t_2} \sqrt{\sigma_s^2 + \sigma_r^2}$$

$$\Delta t_2 = \frac{60}{88} \frac{200}{80} = 1.71 \text{ secs.}$$

$$\sigma_{E_2} \sim 12 \text{ mph}$$

or ~ 15% standard deviation error.

If the intermediate times t_2^m, t_4^m, are not used and only the train entrance into a block calculated,

$$\sigma_E = \frac{\sqrt{2}\quad \overset{o}{V_n}}{t_3^m - t_1^m}\sqrt{\sigma_s^2 + \sigma_r^2}$$

For a 1000' block, $t_3^m - t_1^m = 8.5$ secs,

$$\sigma_E = 2.4 \text{ mph}$$

For a 500' block

$$\sigma_E = 4.8 \text{ mph}$$

and the error is inversely proportional to block length, i.e.

$$\sigma_E = \sqrt{2}\ \sqrt{\sigma_s^2 + \sigma_r^2}\ \ \frac{\ell_n}{(\Delta t_n)^2}$$

b) For the constant acceleration case, using only the data for the entry of the train into a block and the exit of the front of the train from the block, and assuming that the velocity computation is compared to the:

(1) Actual average velocity over the block

(2) The velocity at the time of exit of front of the train from block

$$\overline{V}_3^1 = \frac{\ell_n}{t_3^m - t_1^m + \varepsilon_3 - \varepsilon_1}$$

$$v(t) = v_n^o + a_n^o\ (t - t_1^m)$$

$$\ell_n = v_n^o(t_3^m - t_1^m) + \frac{a_n^o}{2}\ (t_3^m - t_1^m)^2$$

$$t_3^m - t_1^m = \Delta t_n$$

$$\Delta t_n^2 + \frac{2v_n^o}{a_n^o}\ \Delta t_n - \frac{\ell_n}{a_n^o} = 0$$

$$\Delta t_n = -\frac{v_n^o}{a_n^o} \pm \sqrt{\left(\frac{v_n^o}{a_n^o}\right)^2 + \frac{\ell_n}{a_n^o}}$$

$$\Delta t_n = \frac{v_n^o}{a_n^o}\left(\sqrt{1 + \frac{a_n^o \ \ell_n}{(v_n^o)^2}} \ -1\right)$$

1. Now the error between the calculated velocity and the mean velocity is

$$E_1 = \frac{\ell_n}{\Delta t_n}\left(1 - \frac{1}{1 + \frac{\varepsilon_3 - \varepsilon_1}{\Delta t_n}}\right)$$

$$\sim \frac{\ell_n}{\Delta t_n}\left(\frac{\varepsilon_1 - \varepsilon_3}{\Delta t_n}\right)$$

$$E_3^1 \sim \frac{\ell_n}{\Delta t_n^2} \quad \varepsilon_1 - \varepsilon_3$$

$$\sigma_{E_3^1} = \frac{\sqrt{2} \ \ell_n}{\Delta t_n^2}\sqrt{\sigma_s^2 + \sigma_r^2}$$

the same as the error for constant velocity.

2. The velocity at the exit of the block is

$$v_n(t) = v_n^o + a_n^o \ \Delta t_n$$

the error is, then

$$E^* = v_n^o + a_n^o \ \Delta t_n - \frac{\ell_n}{\Delta t_n + \varepsilon_3 - \varepsilon_1}$$

$$= v_n^o + a_n^o \ \Delta t_n - \frac{v_n^o \ \Delta t_n + a_n^o \ \frac{\Delta t_n^2}{2}}{\Delta t_n + \varepsilon_3 - \varepsilon_1}$$

$$E^* = v_n^o + a_n^o \ \Delta t_n - \left(\frac{v_n^o + a_n^o \ \frac{\Delta t_n}{2}}{1 + \frac{\varepsilon_3 - \varepsilon_1}{\Delta t_n}}\right)$$

$$\sim a_n^o \frac{\Delta t_n}{2} - \left(v_n^o + a_n^o \frac{\Delta t_n}{2}\right)\left(\frac{\varepsilon_3 - \varepsilon_1}{\Delta t_n}\right)$$

The first term in the equation above is the error due to discretization. The second term is due to timing errors and yields

$$\sigma_{E*} = \underbrace{a_n^o \frac{\Delta t_n}{2}}_{\text{Discretization}} + \underbrace{\sqrt{2}\left(v_a^o + a_n^o \frac{\Delta t_n}{2}\right)\frac{\sqrt{\sigma_s^2 + \sigma_r^2}}{\Delta t_n}}_{\text{Timing Errors}}$$

The timing errors are the same as for the previous cases but uses the velocity halfway through the block.

3. For the case of exponential acceleration

$$v(t) = v_n^o \pm \tau_n a_n^o \left[1 - e^{-(t - t_1^m)/\tau_n}\right]$$

the discretization errors are

$$\pm T_m^2 a_n^o \left(1 - e^{-\Delta t_n/\tau_n}\right)$$

The timing error standard deviation is

$$\left[v_n^o \pm \tau_n a_n^o \mp \frac{\tau_n^2 a_n^o}{\Delta t_n}\left(1 - e^{-\Delta t_n/\tau_n}\right)\right]\frac{\sqrt{2}\sqrt{\sigma_s^2 + \sigma_r^2}}{\Delta t_n}$$

The above results are summarized in the following Table

STANDARD DEVIATION

	Descretization Error	Timing Error
1. Constant Vel.	0	$\sqrt{2}\,\sqrt{\sigma_s^2 + \sigma_r^2}\;\dfrac{v_n^o}{\Delta t_n}$
2. Const. Acc.	$\dfrac{a_n^o\ \Delta t_n}{2}$	$\sqrt{2}\,\sqrt{\sigma_s^2 + \sigma_r^2}\left(\dfrac{v_n^o + a_n^o \Delta t_n/2}{\Delta t_n}\right)$
3. Expon. Acc.	$\dfrac{\tau_n^2\ a_n^o}{\Delta t_n}$	$\sqrt{2}\,\sqrt{\sigma_s^2 + \sigma_r^2}\left(\dfrac{v_n^o \pm \tau_n a_n^o \mp \tau_n^2 a_n^o/\Delta t_n}{\Delta t_n}\right)$

Where:

v_n^o = Velocity at block entry

$|a_n^o|$ = Acceleration at block entry

τ_n = Time constant

Δt_n = Transit time through block

Example

σ_s = 0.15 sec	σ_r = 0.1 sec.
v_c^o = 50 mph	τ_n = 4 sec.
a_n^o = 2.2 mph/sec.	L_t = 300 feet

	Discretization Error	Timing Error
1. Cons. Vel.	0	3.1 mph
2. Cons. Acc.	1.1 mph	6.9 mph
3. Expon. Acc.	8.8 mph	12.9 mph

APPENDIX E

CHRONOLOGY OF TECHNICAL CONTACTS

DATE	TECHNICAL CONTACT
3/22/73	BART, Oakland, California
4/4/73	BART, Oakland, California
4/30/73	BART, Oakland, California
5/16/73	MBTA, Boston, MA
5/22/73	Gibbs-Hill, New York City, NY
5/29/73	Westinghouse, Pittsburgh, PA
5/30/73	MBTA, Boston/Charlestown, MA
6/6/73	AIRTRANS, Dallas, Texas
6/11/73	BART, Oakland, California
6/14/73	Westinghouse, Pittsburgh, PA
6/17/73	BART, Oakland, California
7/13/73	Siemens Corp., New York City, NY
7/17/73	BART, Oakland, California
7/17/73	Westinghouse, Emeryville, Cal.
7/19/73	Parsons Brinckerhoff · Tudor · Bechtel, San Francisco, Cal.
7/19/73	PATCO, Philadelphia, PA
8/8/73	Westinghouse, Pittsburgh, PA
8/20/73	BART, Oakland, California
8/31/73	NYCTA, Brooklyn, New York
9/5/73	BART, Oakland, California
9/6/73	WMATA, Washington, D.C.
9/7/73	Westinghouse, Emeryville, Cal.
9/10/73	General Railway Signal Co., Rochester, NY
9/12/73	Westinghouse Air Brake, Pittsburgh, PA
9/19/73	BART, Oakland, California
9/20/73	BART, Oakland, California
9/20/73	Westinghouse, Emeryville, Cal.
9/25/73	METRO, Mexico City, Mexico
10/1/73	Westinghouse, Pittsburgh, PA
10/1/73	BART, Oakland, California
10/7/73	Chicago Transit Authority, Chicago, Illinois

APPENDIX F

REFERENCES

SUMMARY

1. Safety Methodology in Rail Rapid Transit System Development NTSB-RSS-73-1, National Transportation Safety Board, Washington, D.C., 20591, August 8, 1973.

SECTION 1

None

SECTION 2

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2. Special Study of Rail Rapid Transit Safety, NTSB-RSS-71-1, National Transportation Safety Board, Washington, D.C., 20591, June 16, 1971.
3. Safety Methodology in Rail Rapid Transit System Developmen NTSB-RSS-73-1, National Transportation Safety Board, Washington, D.C., 20591, August 8, 1973.

SECTION 3

None

SECTION 4

None

SECTION 5

None

SECTION 6

1. Wilson, Ira G., Wilson, Marthann E., From Idea to Working Model, John Wiley & Sons, Inc., New York, New York, 1970.
2. Colella, A.M., Wong, B., Transportation Systems Simulatio Requirements, Proceedings of the Summer Computer Simulati Conference, Boston, Massachusetts, July 1971.
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SECTION 7

1. MBTA Green Line Tests, Riverside Line, December 1972, George W. Neat, Editor, Final Report DOT-TSC-UMTA-74-1, I, Department of Transportation, Urban Mass Transportation Administration, Office of Research, Development and Demonstration, Washington, D.C., September 1973.

2. Friedlander, G.D., BART, The Grand Scheme, IEEE Spectrum, September 1972.

3. Hoyler, R.C., Design Techniques for Automatic Train Control, Westinghouse Engineer, July 1972.

4. Gibson, T.B., Bay Area Transit System Will Have Automated Control, Westinghouse Engineer, March 1970.

5. Hoyler, R.C., Automatic Train Control Concepts are Implemented by Modern Equipment, Westinghouse Engineer, September 1972.

6. Hillman, H.D., Carhins, O.H., The Washington Metro Automatic Train Supervison System, Paper No. 73-ICT-79, American Society of Mechanical Engineers, September 1973.

7. Röhr, Walter, Present Day German Signalling Practice, Railway Technical Review, September 1965.

SECTION 8

1. Human Factors Guide to Equipment Design, McGraw-Hill, 1972.

APPENDIX B

NOTE:

References for Appendix B are included at the end of Appendix B.

APPENDIX C

1. Safety Methodology in Rail Rapid Transit System Development, NTSB-RSS-73-1, National Transportation Safety Board, Washington, D.C., 20591, August 8, 1973.

NOTE:

Numerous other documents were accumulated to become the Automatic Train Control System study team library. Although many of these could probably also be obtained by the general public from the various properties and equipment manufacturers, they are not generally available in libraries or through the commonly used information service centers, and have, therefore, not been listed here.

APPENDIX G

TRANSIT INDUSTRY REVIEW AND COMMENTS

A preliminary version of this document was distributed to 117 selected individuals at 53 different transit properties, transit consultant firms, automatic train control equipment suppliers, etc. requesting review and comment prior to publication approval by the sponsor. As a result, a few typographical corrections and some substantive technical corrections, primarily in Appendices A and B, have been incorporated into this document.

All written opinions representative of different points of view as submitted by the reviewers but not used to alter the text of the report have been only slightly edited, in an attempt to preserve anonymity, and otherwise completely reproduced here. It was felt that inclusion of the comments in this particular form would be an important addition to the document and most beneficial to other readers.

The contribution of the reviewers to the improvement of this document is hereby gratefully acknowledged.

Response 1

I wish to thank you for providing me with a preliminary copy of the report entitled "Safety and Automatic Train Control for Rail Rapid Transit Systems."

As you know, we are planning a rail rapid transit system and therefore are very directly concerned with the contents of this report.

Response 2

Thank you for your recently received copy of, "Safety and Automatic Train Control for Rail Rapid Transit Systems." Your report seems to be the most thorough study of automatic train controls and the attendant communication systems that I have seen for a long time.

I am not the foremost authority on electronics and communications systems and so I cannot make critical comment about your evaluation of electronic systems.

Your abstract and executive summary both seem very concise and appropriate.

Response 3

Members of our technical staff have reviewed the "Safety and Automatic Train Control for Rail Transit Systems" report. Although in some cases we do not agree with your study methodology and all of your data or conclusions, there is nothing specific or of such importance for us to comment on at this time.

We would like to commend you and your staff on the excellence of the study and the positive attitude reflected throughout the report. We also want to thank you for including us in your preliminary distribution for review of the document.

Response 4

The matter of the man-machine interface does not appear to have been developed to the fullest possible extent from the standpoint of the train operator. Criteria should be established to define the types of data which must be available to the operator together with the most effective method of display.

Page x, Summary of Recommendations, paragraph 1A. I suggest you consider adding the statement, "Also, these data are useful for verification of the system safety analyses performed earlier in the system development process.

Page x, paragraph 1B. I suggest you consider finishing the statement with "and may be considered as one of the alternative ways in which the system may react to a component failure."

Response 5

The subject report has been circulated for review and comment Our design and engineering staff report that they can detect no factual discrepancies or errors of a substantive nature in the text. The subject matter of this document is of extreme concern to us and we are grateful for the conduct of this study. I personally feel that the work of your staff which culminated in this report will have a beneficial impact on the design of our system and I wish to congratulate the project team for their efforts.

I am of the opinion that the subject of automation in rapid transit systems and more specifically in train control must be approached on a pragmatic basis. In this respect Appendix B, to the report serves to dispel much of the mystique that heretofore has been associated with automatic train protection. I feel that this appendix and the report in general will materially assist us in resolving the extent of automation to be contained in the train control system.

Let me convey my appreciation for the contents of Appendix A. The summary Characteristics of Existing and Proposed Rail Rapid Transit Systems contained in the appendix provide a quick and consolidated reference for this information which otherwise would take a great deal of time and effort to acquire.

Another comment in which you may be interested concerns right-of-way surveillance. This topic is treated in Chapter 5 of the report entitled, Functional Role of the Human Operator. This is an activity well suited to human performance. In our system a good deal of the right-of-way will lie adjacent to the railroads and system safety has been concerned with neutralizing the potential safety hazard posed by having derailed railroad cars or material from them encroach upon our right-of-way. One current proposal under consideration is to provide an automatic encroachment detection system along the joint right-of-way just for this purpose. Thus right-of-way surveillance would be accomplished both on an automated and manual or human basis.

I was happy to see you clarify and expound upon the "fail-safe" concept as applied to train control. We were never of the opinion that the NTSB actually intended that their recommendation on this point in their report be interpreted as total abandonment. Your report clarifies this matter when you state, "Conclusions elsewhere in this report suggest the inadequacy of the fail-safe concept, by itself, and underscore the desirability of fail-safe operational capability, with graceful degradation characteristics at the system level, and the merit of having levels of surveillance capability."

Let me conclude by saying the report raises more questions than it answers. I am sure this was intentional. There is a great deal of pithy material presented which must be digested before solutions can begin to be formulated to the questions you have raised.

Response 6

I think it is not possible, and probably not desirable, to define factors of safety, with increasing automation, in wholly theoretical values. Therefore, I believe it would be desirable to amplify this theoretical study by another report, prepared by practical railway signal engineers, both from USA and overseas.

I think the problem is compounded because of the built-in tendency to introduce evermore complication, and, therefore, cost. No one holds a brief for simplicity.

Response 7

This report does an excellent job in accomplishing two functions: (a) it helps to inform persons without railroad oriented backgrounds in the safety and reliability aspects of railroad types of equipments, (b) it helps to inform persons with railroad oriented backgrounds on reliability engineering techniques used in the aerospace industry that have not as yet been systematically applied to the railroad control field. There are a few aspects that you may wish to give further attention in your continuing works in this area. A number of engineering considerations affecting safety and reliability of railroad control systems have escaped mention in the report or may have merely escaped my notice. I do not regard their omission as a "factual discrepancy or error of a substantive nature" that would necessitate delaying publication of this report. However, since as I understand your work is an ongoing effort, my comments may be of use to you in your future activities.

When discussing the engineering aspects of railroad control systems and their effects upon safety and reliability, several factors come to my mind:

1. Electromagnetic radiation effects and direct strikes of lightning during electrical storms can reduce reliability and possibly impair safety, unless the equipment is properly designed and maintained. This is increasingly important as more and more semiconductor and LSI equipments with low breakdown voltages and high data bit rates are introduced into new technology systems. Of corollary importance is proper maintenance of ground rods and prevention of unwanted circuit grounds. Having performed extensive field tests of lightning protection, I can emphasize how quickly and unexpectedly lightning protection can deteriorate if grounding has not received proper maintenance attention.
2. Adjacent high voltage commercial power lines must also be considered. This consideration must include both the effects of the commercial frequency electromagnetic field effects, and the radiation of higher frequency electromagnetic noise generated by power company customers.

3. I recall instances of "foreign current" through earth ground from nearby commercial power systems entering our signal system and requiring that I give special design attention to prevent unsafe operation to our automatic train stop and highway crossing protection.

4. Permanently magnetized wheels have been the attributed cause of a C&NW passenger train collision. The wheels were handled by magnetic cranes and unknowingly became magnetized. This hazard should be recognized in safety and reliability programs.

5. Unless proper design attention is given, synchronous slip of wheels in an automatic train operation system can go undetected and give a false speed signal.

6. Ferromagnetic materials in the lining of subway tunnels can attenuate signals used to detect track occupancy. It is important to give this proper consideration in the design and testing stages, thereby preventing potential problems of safety and reliability in the future.

7. In future works, you may wish to cite these additional technical references: Railway Systems and Controls, a monthly trade journal published by Simmons-Boardman Publishing Company, 508 Birch Street, Bristol, Connecticut, 06010, and Rules, Standards, and Instructions for Railroad Signal Systems published by the Federal Railroad Administration, Bureau of Railroad Safety.

I hope you will find these comments of interest and use in the continuing work you are doing in the field of safety and reliability of automatic train control systems. Thank you again for the opportunity to review your thorough report.

Reponse 8

Thank you for your letter forwarding a copy of the report "Safety and Automatic Train Control for Rail Rapid Transit Systems". This document is an excellent compilation on the subject of Automatic Train Control and will prove to be a useful contribution to the transit industry.

I regret that time to date has permitted only a cursory review of the report, which brings two comments to mind:

1. There is an apparent absence of user input in the report, particularly in the application of automatic systems to existing rail transit operations. The need, level of automation and the resulting benefits to an operating system warrant study.
2. I cannot accept the idea of abandoning per se the "fail-safe" concept as recommended in the recent N.T.S.B. study. There is a common error often made in confusing reliability with safety. These two items are not synonymous. Passenger safety must be foremost even at the expense of reliability.

As stated previously these comments are the result of a scan review of the document. A more detailed study may prove that my initial reaction is in error.

Response 9

The subject report analyzes the safety and operational requirements for automatic train control on rapid transit systems. It presents several new concepts for consideration, the most significant of which makes "operational availability" an end, and system safety design a means to achieve that end.

I am concerned when DOT sponsors a report on a concept which relegates safety subordinate to "operational availability" (keeping trains moving). Several references are made in the subject report to National Transportation Safety Board Report NTSB-RSS-73-1 "Safety Methodology in Rail Rapid Transit System Development", which recommended the abandonment of the concept of fail-safe design for rail rapid transit systems in favor of modern, effective system safety management and safety analysis methods.

Referring to the above, the subject report (on Page VIII) does state "Such a major step would have to be taken with great care, and it would be important to provide the mechanism for such a change." I cannot agree more strongly. However, the caution appears to be ignored. In Appendix C, on Page C4, it is concluded that "the fail safe concept by itself is an inadequate automatic train control system design criterion for ensuring high levels of overall system safety and operational availability."

Our signal system is based on a fail-safe design and should continue to be so designed. "Effective system safety management and safety analysis methods," as they become available, should be used as tools to achieve and verify fail-safe design, not to replace it. The fail-safe principle does not impede "operational availability," as implied in the subject report; component failure does.

By approving only contractors and suppliers with a demonstrated history of successful performance in railway signaling we have minimized the incidence of component failure and achieved high operational availability in combination with fail-safe design.

The subject report disagrees with this approach. The following paragraph appears on Page 8-10:

"The fail-safe criterion also has a restrictive effect on the application of new technology to rail rapid transit control systems. A new component development to be approved fail-safe must be installed and used extensively in a system as part of the approval process. Generally, new systems only employ components already judged fail-safe. As a result of this closed, self-perpetuating process, the set of fail-safe components and their manufacturers has not changed significantly for many years. Standards and procedures must be established so that new technology, components and subsystems can be objectively evaluated and made available as designer options."

It appears that the "new technologies, components, and subsystems" are not compatible with fail-safe design, and if so applied, "operational availability" will be diminished. Therefore, fail-safe design is made subordinate to "operational availability."

Although several of the concepts presented warrant further study, the safety recommendations respecting fail-safe design are in such direct opposition to our own design philosophy, that I recommend exception to be taken thereto.

Response 10

I really appreciate receiving this fascinating document and I must say it is a very professional job. As you probably are aware, I became involved when I registered a protest to the recommendation from the National Transportation Safety Board that all rail and rapid transit systems "abandon the fail-safe concept."

Your report makes far more sense, namely to use fail-safe as one of the building blocks in the overall plan.

Keeping in mind your request that I confine my comments to factual discrepancies and errors of a substantive nature, I find as follows:

1. Paragraph 2.1.1.f.

   The term guard rail as used in this section is apparently intended to mean fencing. Guard rail in railroad terms means an additional rail or rails at switch locations and on bridges and elevated structures to control derailments.

2. Control System Design - Paragraph 6.1 - Page 6-5.

   In real world train operations there is no reason to consider single track operations hazardous, nor is there any excuse for compromising safety in non-normal event control situations.

   The second paragraph on this page is theoretically correct, but idealistic because invariably the cost factor of including provision for growth will take precedence over logic.

3. Recommendations - Paragraph 8.2.16 and 8.3.3 - Pages 8-9 and 8-12.

   Typical of several locations in the study is the statement that this "program should be a requirement for any federal or other public funding process." This implies that if you have money enough to do the job without public funding, it will be all right to disregard any of these requirements. Obviously, if the requirements are necessary to protect the public, then no certification should be issued unless there is compliance. The inference that can be taken is that this whole approach is an arm-twister by the Federal Government to indicate that "we <u>want</u> you to do it this way and if you don't agree, we won't give you any money."

4. <u>Paragraph 8.3.18 - Page 8-26 last paragraph.</u>

   It is stated that special procedures are required to ensure that such non-normal operation cannot bypass or override any safety system. The exact opposite is true. Special procedures are required to permit non-normal operation by the use of a bypass or override in the hands of a qualified operator to keep the system functioning until the defective equipment is taken out of service.

5. <u>Appendix B-1 - Page B-5</u>.

   The statement in the last sentence is not quite accurate. Currently, traffic loads on the Long Island Railroad are peaked at about one train every two minutes and to operate to Penn Station, New York, they also must groove in with conventional Penn Central and Amtrak trains in certain areas. Studies are currently under way to add Erie-Lackawanna traffic from New Jersey to the Penn Central traffic, signalled for 90 second headway and maximum speeds of 90 MPH for certain types of equipment. I cannot envision any greater need to transmit accurate information on identity and location than this operation. Since older types of equipment not readily adaptable to ATO will be using the same tracks with new style equipment, the result will probably be manual control of all trains.

6. Appendix B-2 - Page B-6.

The first statement is in error. Signaling is not only used for avoiding collisions. On many properties, signals indicate not only the condition of the block (clear or occupied) but also indicate the speed that the train must conform to and/or the route that the train will take at points of diversion. The statement in the second paragraph that the modern equivalent of this procedure allows a train to enter a single line section on a clear signal only is also in error. A train can follow another train into a block under a restricitng or stop and proceed signal on tracks so equipped.

Unfortunately the starting signals are not always electrically interlocked to avoid opposing movements.

7. Check No. 2 (Page B-6).

Indicates that all surveillance systems must contain block overlaps and while this is true of most rapid transit systems, it is very seldom true on standard railroads, some of which operate commuter trains on headways as close or closer than rapid transit systems.

The statement at the end of Page B-7 that "the absolute quality assumed is illusory "is vague and ambiguous and appears to have no basis in fact."

8. Appendix B-3 - Page B-8.

The last paragraph consists of a lot of fancy double-talk which doesn't give one specific constructive suggestion for a substitute for the "fail-safe principle."

9. Appendix B-9 - Page B-62.

Failures of track circuit insulators cannot result in power from an adjoining block keeping the green lamp lit because of staggered polarity.

10. Summary - Page B-65.

The statement is made that "all commands should be verified at the command origin." Assuming a computer controlled system, this is one of the inherent weaknesses from a reliability standpoint, because if there is any disruption in the communication link between the computer and the wayside or on-board equipment the result is the system comes to a halt, or if not designed fail-safe continues to operate in an unsafe manner. There are systems in operation where local wayside equipment at interlockings pick up the identification of an approaching train and then route it correctly. It functions properly regardless of breaks in communication to the control center. This is an example of reliability that is needed.

11. Appendix C - Page C-3.

The first paragraph implies that manual operation to remove defective equipment or to permit continued operation creates additional risk. This statement indicates a total lack of understanding of how such operations are carried out. It may be true on BART, but it certainly isn't the situation on other rail lines. For example, complete failure of on-board cab signal and speed control apparatus on Penn Central or Long Island trains requires only that the train operator notify the control center and obtain permission to proceed as a non-equipped train. In wayside signal territory, it may proceed at speeds as high as 79 miles per hour by keeping clear of occupied blocks. In territory with no wayside signals it may proceed at the same speeds but must not accept anything less than a clear signal at each interlocking and that signal must not be cleared by the control point unless there are no trains between that interlocking and the next one in advance.

12. D6 - Page D-15.

Statement is made that command speeds are constant within any one block. Such is not the case. Simulation studies are currently being progressed using signal conceptuals that permit updating speed commands to a train within a block based on the progress of the preceding train.

Response 11

Thank you for the opportunity to review your new document entitled, "Safety and Automatic Train Control for Rail Rapid Transit Systems." This is a timely treatment of the subject and as you said, is of great interest to the transit properties, as well as to the transit community. As a carbuilder our interest is evident in that we have had people working in this subject area for some time. From this experience, we can generally agree with your conclusions and recommendations. In particular, our experience supports your recommendation that accident and incident data collecting processes must be unified and upgraded, and that developmental efforts should be supported in areas of train surveillance subsystems with increased continuity and reliability, and supported in the area of alternate means to cope with subsystem failures other than simply stopping the trains.

In a different view, your report is a good collection of the issues, logic and related material in a central source. It provides a good summary of data which otherwise would require extensive library study and search on the part of those who must assess the issues and establish new policies and practices.

We have for some time encouraged the use of technical specifications and performance specifications in the study, design, procurement and operation of rail vehicles and so endorse your recommendation in that regard.

As one minor point, on page C-8, you suggest requiring the use of failure modes and effects analysis for multiple failures. We believe that reliability fault logic modeling or fault tree analysis would do as well or better!

Response 12

We have reviewed the Preliminary Report "Safety and Automatic Train Control for Rail Rapid Transit Systems". I apologize for the lateness of this letter, but due to vacations, etc., we were not able to get our comments formalized until recently.

The following are our comments. I might add, that we appreciate the opportunity to review the report prior to its release.

Comments: (Relating to factual discrepancies or errors of a substantive nature)

1. Control System Design Requirements, Page 6-5, Par. 6.1

   Single track operations impose no hazard with a properly designed signal system.

2. Signaling Fundamentals, Page B-6, Par. B2

   The statement that "if only one train occupies a section of track, there is no need for signaling" ignores other major functions of a signal system. In addition to the function of assuring safe train separation a signal system assures compliance with safe civil speed restrictions; indicates the route established through interlockings, and checks that all switches in the route are locked to prevent operation when the train is approaching or is on the switch.

   The statement that the provision of an overlap to provide braking distance for a train that over-runs a block may be ignored on a rapid rail system is not factual. An adequate overlap is essential to all train-stop equipped signal systems.

3. Fail-Safe Communications, Page B-62, Par. B9

   A failure of a "track circuit insulator" (insulated joint) cannot falsely energize a track relay in an adjacent block if the track circuit polarities at the feed end are properly staggered.

In the diagram on Page B-63, an essential resistor between the track power supply and the rail has not been indicated. Further, Federal Railroad Administration rules prohibit grounding of signal circuits as indicated for the signal lighting circuit.

4. ATO System Safety Criteria, Page C-3, Par. 1

    The statement that moving trains through "interlocks" creates additional risk is not factual. A properly designed interlocking assures that conflicting or opposing train movements cannot be established.

5. General

    Throughout the report the term "interlock" is employed; the correct railroad signal term is "interlocking".

Although opinions concerning the recommendations have not been solicited, the use of redundancy and hierarchical control concepts are not compatible with system reliability; increase costs of construction and maintenance, and offer no fail-safe protection that cannot be achieved with a properly-engineered and maintained conventional signal system.