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OPERATION OF HIGH SPEED PASSENGER TRAINS IN RAIL FREIGHT CORRIDORS

Robert K. Abbott

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16. Abstract

A preliminary examination of the problems associated with mixed-traffic operations — conventional freight and high speed passenger trains — is presented. Approaches based upon a modest upgrading of existing signal systems are described. Potential costs to the operating railroads, impact on railroad efficiency, and safety of passengers and train crews are considered. Special attention is given to analysis of stopping distancc for various conditions and rolling stock. Basic conclusions are that speeds above 125 MPH are likely to require substantial signal system modification and that freight service capacity will be severly degraded by large numbers of HSPT's; further analysis is required to determine well-founded control-system guidelines.

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PREFACE

The work described in this report was performed in the context of an overall program at the Transportation Systems Center to provide a technical basis for the improvement of rail safety and efficiency. The objective of this project was delineation and examination of the major factors constraining combined operation of passenger and freight service in high-traffic rail corridors. The program is sponsored by the Freight Service Division, Office of Research and Development, Federal Railroad Administration. The study was carried out by the author under the overall direction of John B. Hopkins, whose suggestions and comments have been most helpful. The following Raytheon Service Company personnel assisted in the preparation of this report: Ronald Karr, Technical Editor; Conni Sergerstedt and Mary Melo, Technical Typists; and the Art Department, Gene Adelezzi, Director.

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1. INTRODUCTION

1.1 BACKGROUND

Foreign railroad experience, as in Japan and Europe, indicates that if a commitment is made to completely new roadbed, track, structures, rolling stock, and signal and control systems, safe, comfortable and reliable passenger service at speeds of 125 MPH or greater is possible, and can achieve substantial consumer acceptance. Major advances have been made in the area of on-board equipment for passenger trains, particularly with regard to braking and acceleration capabilities, suspensions, and aerodynamics. Although high-quality track structures and sophisticated control systems are well within the limits of technical feasibility, they are typically not characteristic of potential HSPT corridors in the United States.

The cost of complete line reorganization to render a physical plant fully suitable for high speed passenger train (HSPT) service — completely new signaling and control systems, curve realignments, right-of-way fencing, etc. — has been estimated to be between 0.2 and 1.2 million dollars per mile for some corridors, and the cost for the signal revisions alone has been estimated at between $30,000 and $500,000 per mile, depending in part upon the sophistication of the control system.

Thus, problems arise when attempts are made to provide high speed rail service utilizing existing facilities during consumer acceptance or demonstration operations for which full-scale reorganization of the line is not possible. The determination of maximum train speeds feasible without a major commitment to upgrade the physical plant is a problem being studied throughout the world.[1]

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[1] U.S. Department of Transportation Report, Improved Passenger Service for the Northeast Corridor Pan-Technology Consulting Corp., Report FRA-ORD&D-74-3, April 1973;

U.S. Department of Transportation Report, Improved Passenger Service for Three Corridors, Pan-Technology Consulting Corp., Report FRA-ORD&D-74-4, April 1973.

(continued)

Advanced rolling stock can readily be used on a temporary or trial basis, but this is obviously not true of fixed plant such as improved track and signal systems. Within this constraint, full-scale reconstruction of track and roadbed is precluded. However, if it is assumed that the rolling stock and track structures in a particular case will permit operation of high speed passenger trains, it remains necessary to consider the form and potential costs of the signal and control system necessary to assure safe operation at desired speeds. A second consideration of particular importance to trial or demonstration situations is the impact of HSPT service on freight traffic moving in the same corridor.

1.2 OBJECTIVE

The overall objective of this study is examination of both factors in sufficient depth to permit a general assessment of the magnitude of the problems involved. A brief review of the principles of block signal systems (virtually universal in the U.S.) is accompanied by a description of factors affecting train stopping distances, including discussion of various means of meeting the signaling requirements necessary to the safe and efficient operation of HSPT's. The several recognized classes of train control systems are summarized, and FRA data are analyzed to provide a measure of the level of safety — and safety benefits — attainable through automatic train control systems. The question of the impact of HSPT's upon freight service operations is addressed in a generalized manner through train graph analysis applied to several specific, though idealized, cases. Recommendations based upon the study are then summarized.

(Continued)

J.W. Diffenderfer, "High Speed Passenger Transportation in the Northeast Corridor of the United States of America Utilizing Existing Facilities," presented at the I.R.C.A. — U.I.C. High-Speeds Symposium, Vienna, 1968.

J.L. Cann and J.T. Wilson, "Development of a High Performance Train System for the Toronto-Montreal Corridor," presented at the I.R.C.A. — U.I.C. High-Speeds Symposium, Vienna, 1968.

1.3 SCOPE

As indicated above, the primary focus of this study is signal and control aspects of HSPT operation, with safety and efficiency as criteria. Other elements of physical plant, such as roadbed requirements and costs, and adequate grade crossing safety,[2] are not treated in this study.

This examination does not include surveys of specific rail corridors. The study is based upon two general assumptions which appear to be realistic for U.S. operations:

1. All potential demonstration high speed HSPT routes will be in existing rail corridors and over existing high density rail lines – routes likely to be characterized by approximately 40 or more trains per day. (For example, on the rail corridor between New York and Washington there are about 570 train origins per day. A "snapshot" look at the traffic on that corridor at 5:30 pm would find about 45 passenger and 10 freight trains.)
2. Existing rail lines have been operated and designed – in terms of signaling, curvature, rail, etc. – primarily for freight traffic.

It is to be noted that site-specific surveys are especially important in assessing the problem of freight train congestion caused by interference from high speed passenger train operation. Studies of this type, with specific consideration of four potential corridors, have been prepared by Pan-Technology Consulting Corp. for the Federal Railroad Administration.[3]

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[2] The subject of grade crossing protection is not examined here and is only mentioned peripherally. For a more complete discussion see:

J.B. Hopkins, Grade Crossing Protection in High-Speed, High Density, Passenger-Service Rail Corridors, Report FRA-ORD&D-74-14, September 1973.

[3] Improved Passenger Service for Northeast Corridor, Op. Cit.; Improved Passenger Service for Three Corridors, Op. Cit.

2. BLOCK SIGNAL SYSTEMS

2.1 INTRODUCTION

The basis of virtually all railroad signal/control is the block system, in which the railroad network is divided into specific segments — "blocks" — which may range from hundreds of feet to several miles or more in length. In general, if a block is occupied by a train, other trains are either forbidden to enter, or may do so only at a speed which permits stopping within sight distance. Such a system can be based upon manual control by railroad employees who communicate train entrance and exit information to one another and set signals accordingly, or by actions of a dispatcher. However, any significant volume of traffic generally warrants use of an automatic system utilizing track circuits, in which each block is isolated electrically from adjacent segments. The electrical short-circuit between rails caused by the wheels and axles of an occupying train is readily detected and can operate a signal system without direct human intervention. In more sophisticated systems, a block entrance signal can also be controlled by the occupancy condition of one or more blocks in advance of the one in question, in what is referred to as a "multi-aspect" signal system, illustrated in Figure 2-1. In this way an engineer can be informed, for example, that the block he is entering is vacant, but that the next block is occupied, which could imply a second train stopped just inside the entrance to the second block. A clear and comprehensive review of this subject can be found in Armstrong's <u>All About Signals</u>.[4]

All high density rail corridors in the U.S. include an automatic block signaling system. Approximately 50% of all the track mileage, and approximately 95% of all the multiple track mileage in the U.S., has an automatic block signaling system presently installed.[5] The safety and operating efficiency benefits of automatic block signaling have been appreciated by the railroad industry

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[4] John Armstrong, <u>All About Signals</u>, Kalmbach Pub. Co., 1957, 26 pp.

[5] Unpublished Statistics compiled by the Federal Railroad Administration, Office of Safety, 1973 data.

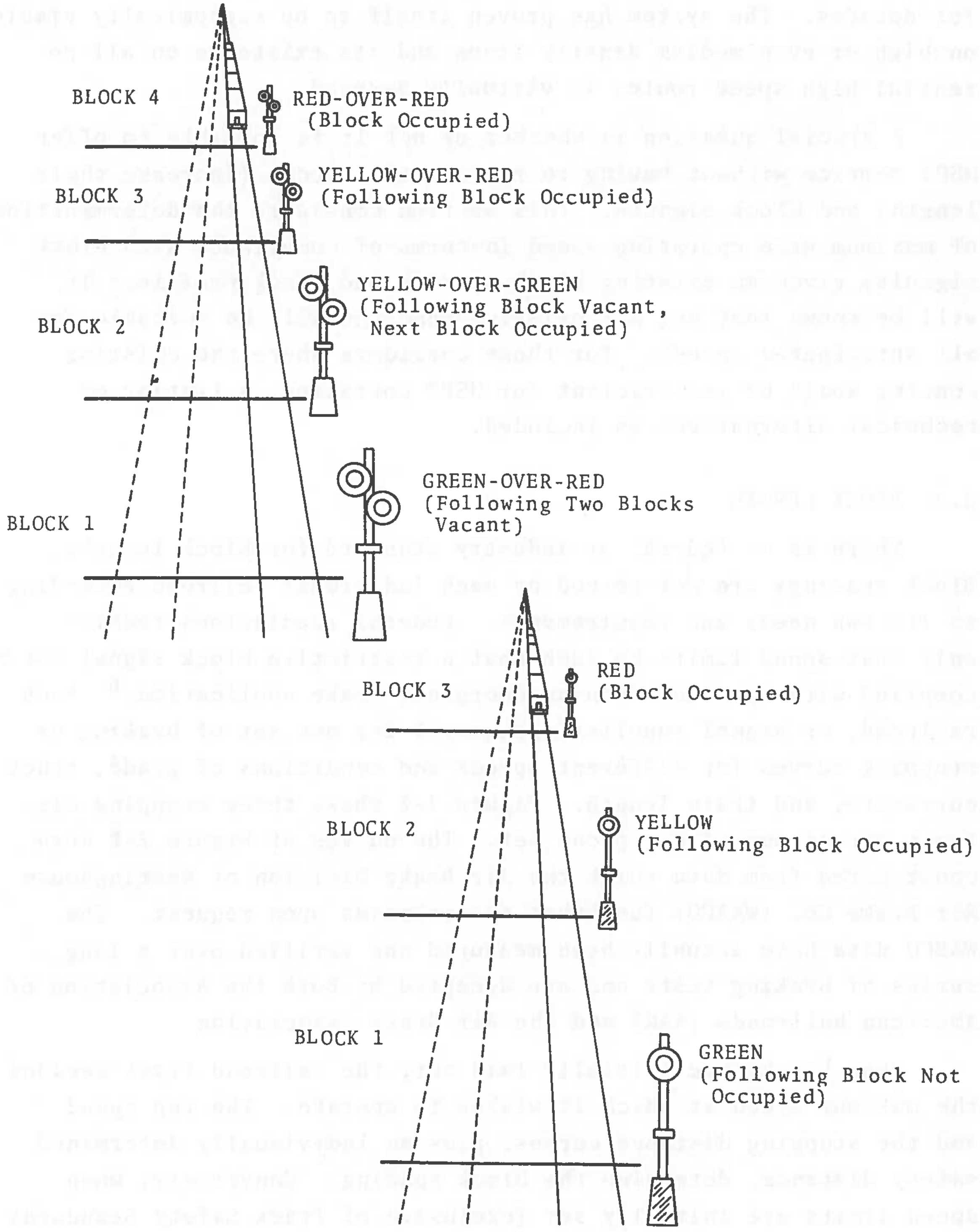

Figure 2-1. Illustrations of Possible Three-Aspect and Four-Aspect Signal Systems

for decades. The system has proven itself to be economically viable on high or even medium density lines and its existence on all potential high speed routes is virtually assured.

A crucial question is whether or not it is possible to offer HSPT service without having to respace the blocks (increase their length) and block signals. This section considers the determination of maximum safe operating speed in terms of compliance with block signals, given an existing block spacing and track profile. It will be shown that not all existing spacings will be suitable for all anticipated speeds. For those corridors where the existing spacing would be insufficient for HSPT operation, a listing of technical alternatives is included.

2.2 BLOCK LENGTH

There is no Federal or industry standard for block lengths. Block spacings are determined by each individual railroad according to its own needs and requirements. Federal regulations require only that speed limits be such that a restrictive block signal can be complied with by other than an emergency brake application.[6] Each railroad, or signal supplier, generates its own set of braking or stopping curves for different speeds and conditions of grade, track curvature, and train length. Figure 2-2 shows three stopping distance curves out of a typical set. The curves of Figure 2-2 were constructed from data which the Air Brake Division of Westinghouse Air Brake Co. (WABCO) furnishes to railroads upon request. The WABCO data have actually been measured and verified over a long series of braking tests and are accepted by both the Association of American Railroads (AAR) and the Air Brake Association.

When blocks are initially laid out, the railroad first decides the maximum speed at which it wishes to operate. The top speed and the stopping distance curves, plus an individually determined safety distance, determine the block spacing. Conversely, when speed limits are initially set (exclusive of Track Safety Standards or other considerations), the block spacing and the safety distance

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[6] Code of Federal Regulations, Title 49, part 236.24 (1974).

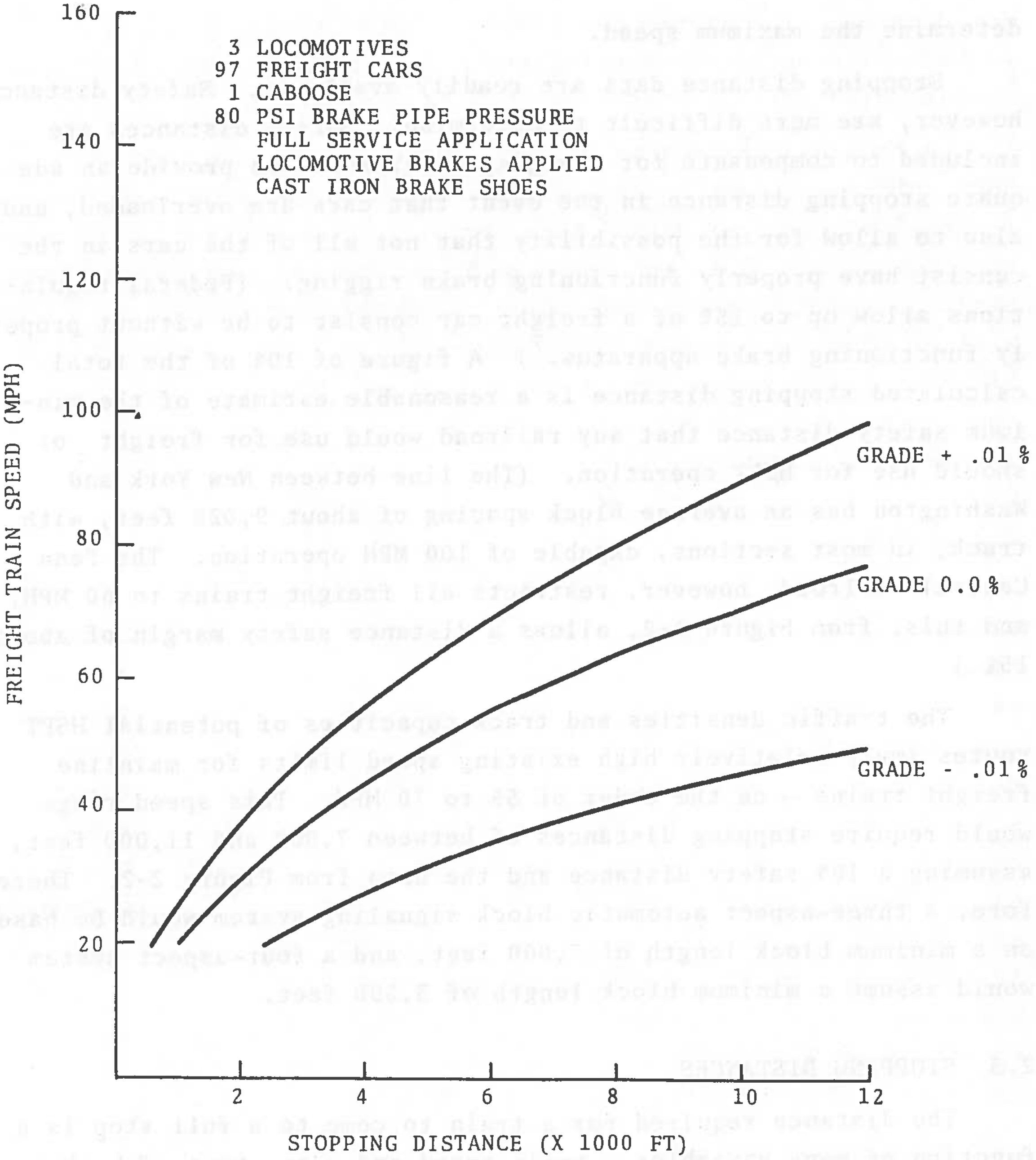

Figure 2-2. Typical Braking Curve for a 97 Car Freight Train

determine the maximum speed.

Stopping distance data are readily available. Safety distances, however, are more difficult to determine. Safety distances are included to compensate for changing conditions, to provide an adequate stopping distance in the event that cars are overloaded, and also to allow for the possibility that not all of the cars in the consist have properly functioning brake rigging. (Federal regulations allow up to 15% of a freight car consist to be without properly functioning brake apparatus.[7]) A figure of 10% of the total calculated stopping distance is a reasonable estimate of the minimum safety distance that any railroad would use for freight or should use for HSPT operation. (The line between New York and Washington has an average block spacing of about 9,020 feet, with track, in most sections, capable of 100 MPH operation. The Penn Central Railroad, however, restricts all freight trains to 60 MPH, and this, from Figure 2-2, allows a distance safety margin of about 15%.)

The traffic densities and track capacities of potential HSPT routes imply relatively high existing speed limits for mainline freight trains — on the order of 55 to 70 MPH. This speed range would require stopping distances of between 7,000 and 11,000 feet, assuming a 10% safety distance and the data from Figure 2-2. Therefore, a three-aspect automatic block signaling system would be based on a minimum block length of 7,000 feet, and a four-aspect system would assume a minimum block length of 3,500 feet.

2.3 STOPPING DISTANCES

The distance required for a train to come to a full stop is a function of many variables — train speed and size, type of brakes, topography, weather, condition of tracks, etc. This subject is reviewed in some detail in the appendix, with special empahsis on limitations arising from braking systems, wheel rail adhesion, and

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[7] Code of Federal Regulations, Title 49, part 232.1 (1974).

passenger comfort. Results from this treatment will be used below to provide a measure of attainable system performance for various cases.

Figure 2-3 shows the nominal stopping distances of the Metroliner and a 97 car "typical" freight train, and the calculated stopping distances of a hypothetical HSPT, based upon the adhesion demand limitations described in the appendix. Figures 2-4 and 2-5 show the stopping distances for the same trains on a -1% and +1% grade, respectively. The stopping distances of the freight train are as would be measured, but the calculated HSPT stopping distances are somewhat longer than would usually be measured. Air resistance or aerodynamic drag would have the effect of decreasing the total stopping distances (from 150 to 0 MPH) by about 20% (assuming a four coach Metroliner or Turbotrain-type train). However, the braking contribution of aerodynamic drag cannot always be counted on, since a strong (50 to 60 MPH) tail wind would diminish the effect by about 70%.

Figure 2-6 shows the maximum safe HSPT speed as a function of the freight train speed for which the signal system has been determined, for three grade conditions. Worst-case adhesion limits are assumed, as described in the appendix. For level, descending, or only slightly ascending track, 125 MPH operation with existing block spacing is seen to be generally feasible. There is a problem, however, on steeply ascending grades, as the decelerating effect of the grade is greater for heavy freight trains than for lightweight HSPT's.

The cost of complete signal re-spacing has been estimated at about $20,000 per mile.[8] This estimate is probably somewhat low if one adds in the cost of new centralized train control (CTC) equipment, new grade crossing configurations, etc. For most corridors, this cost, as well as the time delays to be encountered while the respacing work is being completed, can be eliminated if speed limits of 125 MPH are acceptable.

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[8] Improved Passenger Service for Northeastern Corridor, op. cit.; Passenger Service for Three Corridors, op. cit.

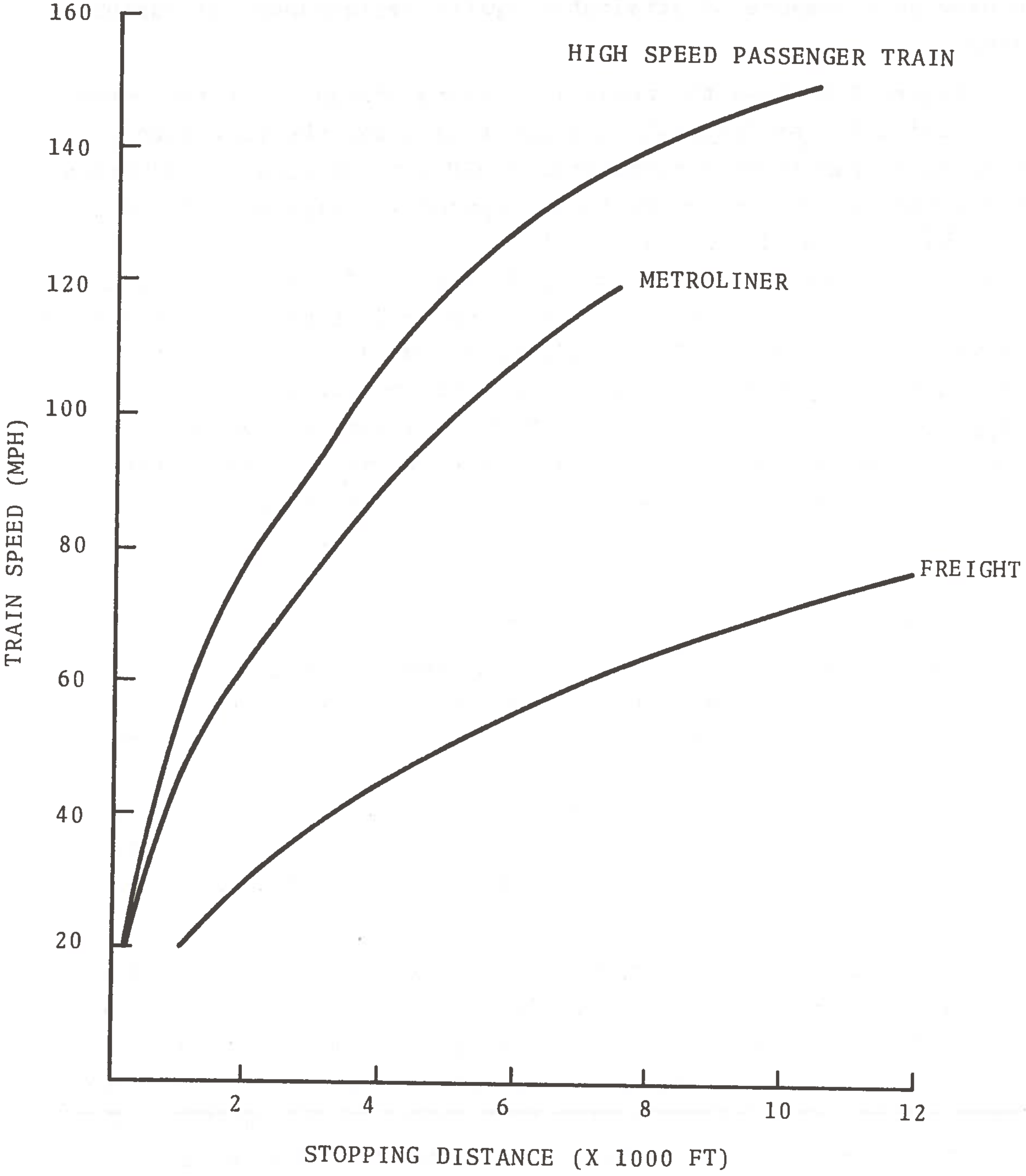

Figure 2-3. Stopping Distances on Level Terrain

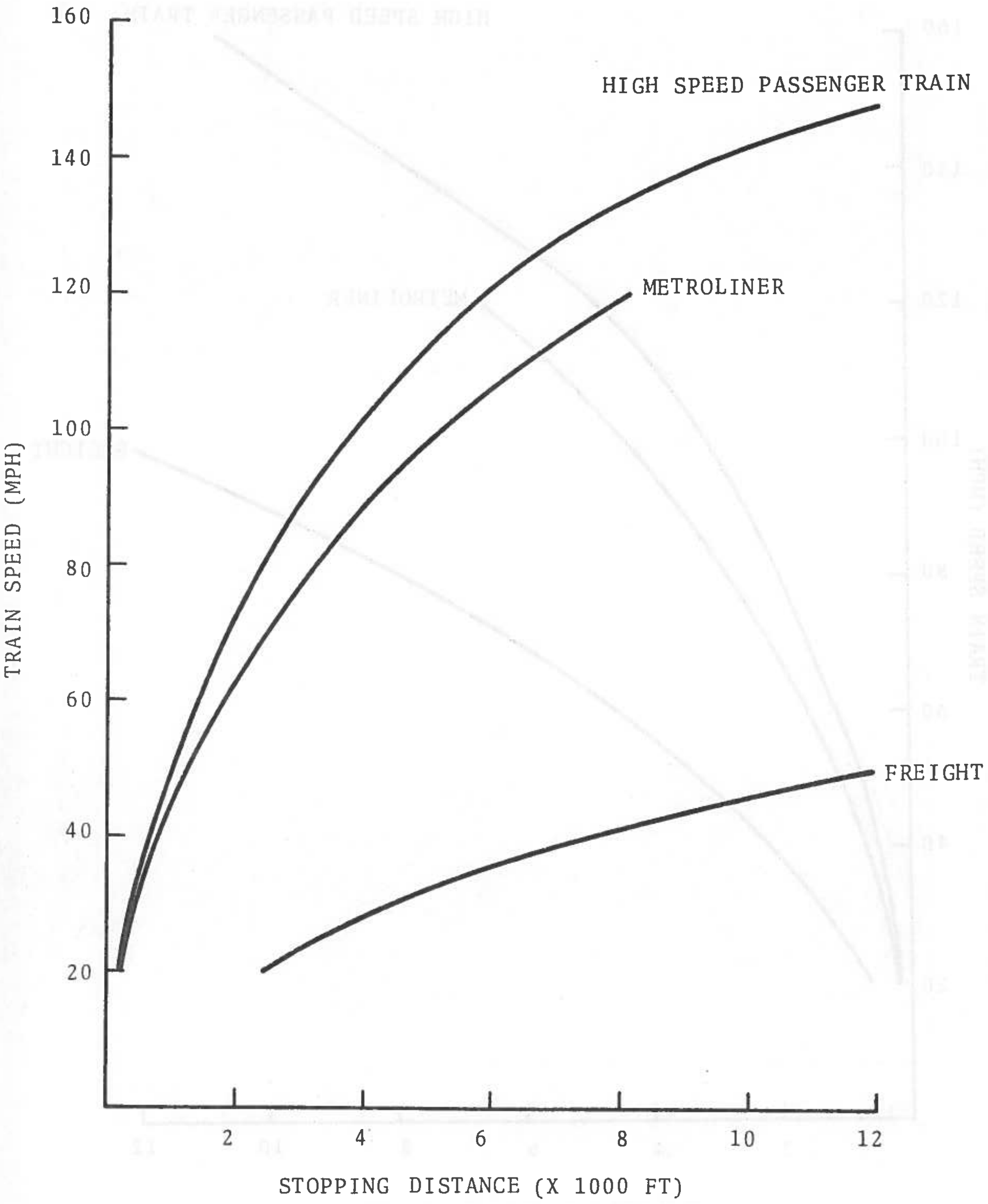

Figure 2-4. Stopping Distances, -1% Grade

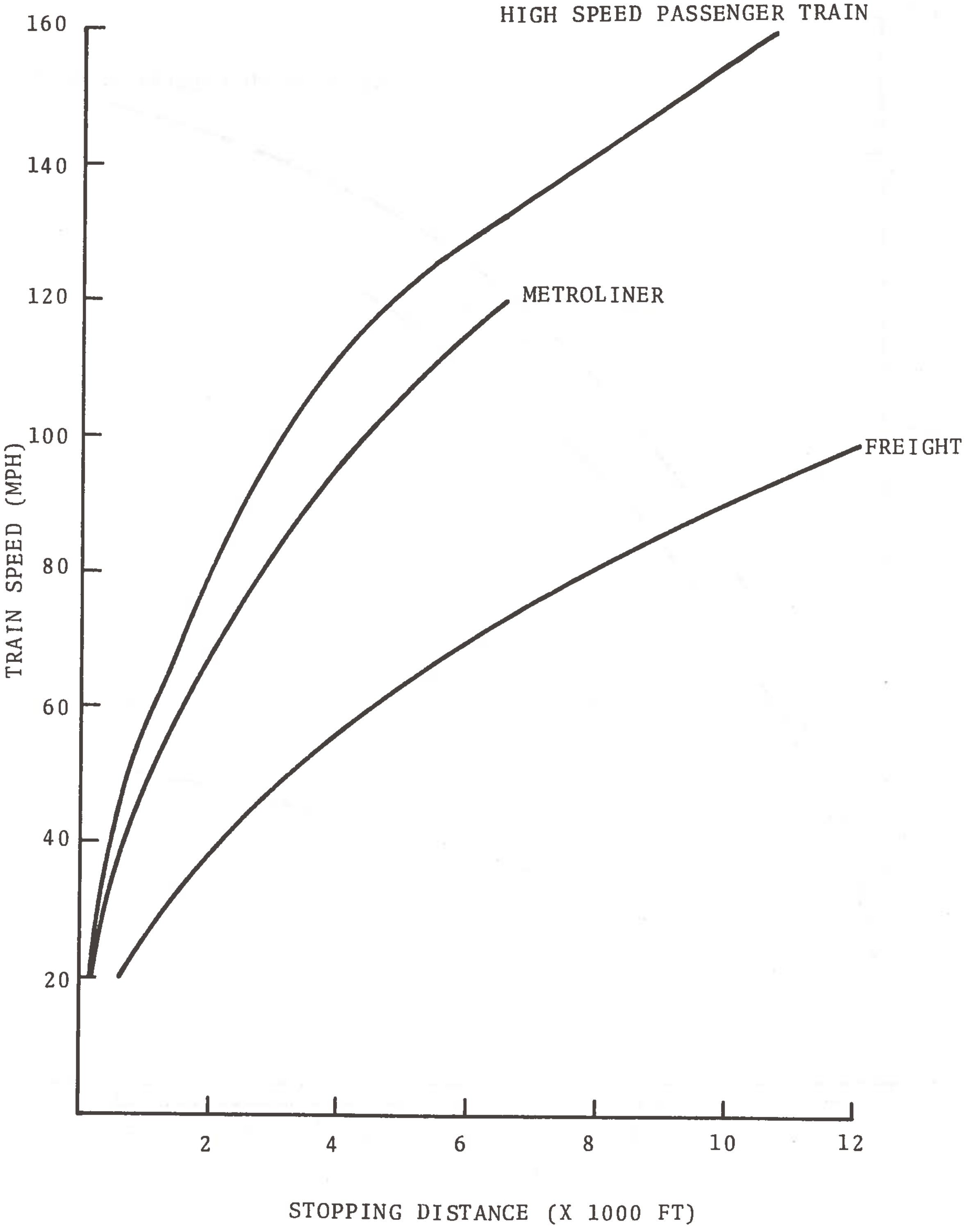

Figure 2-5. Stopping Distances, +1% Grade

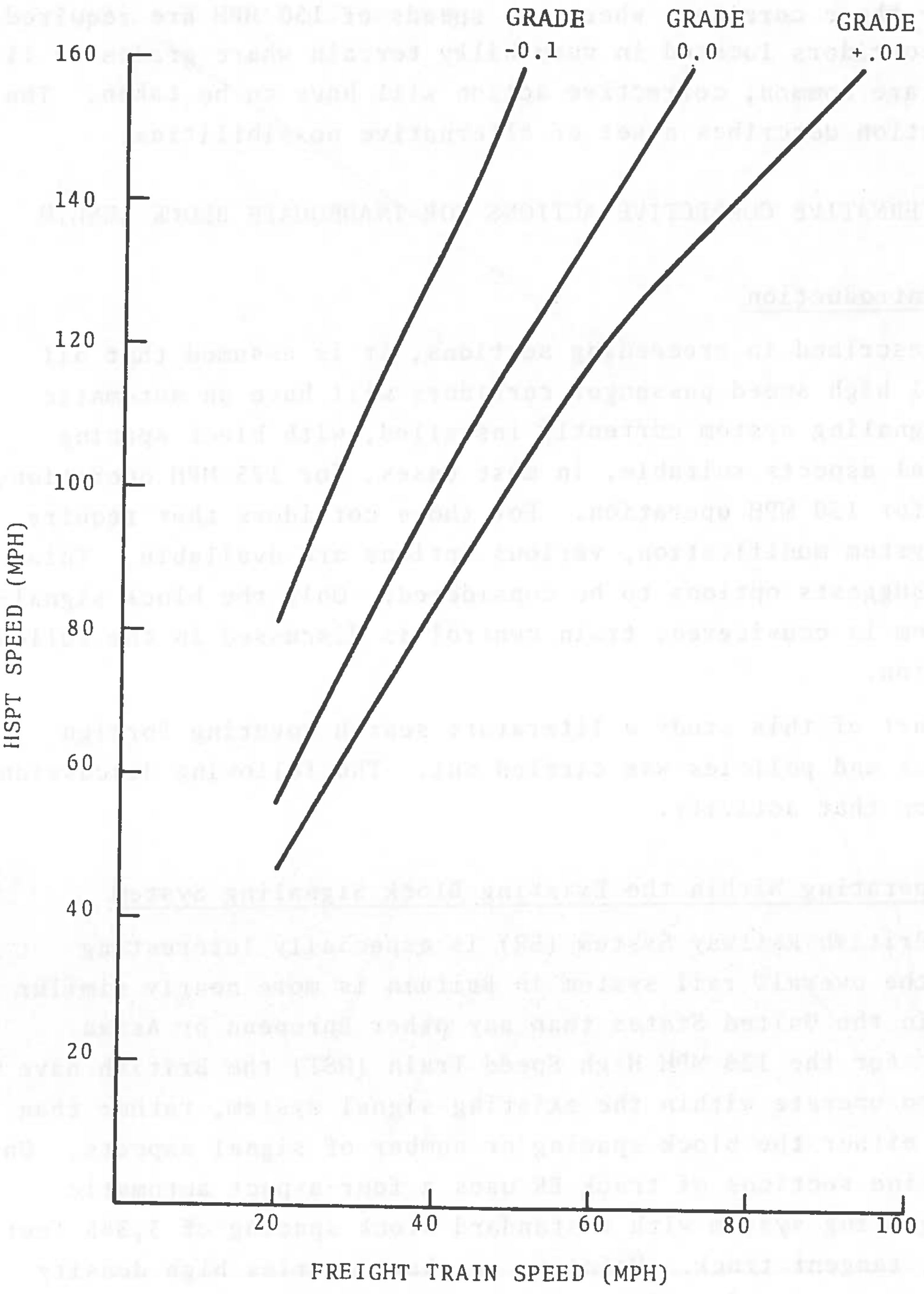

Figure 2-6. Maximum Allowable HSPT Speed as a Function of Freight Train Speed Limit, as Determined from Block Length

For those corridors where top speeds of 150 MPH are required, or for corridors located in very hilly terrain where grades of 1% or more are common, corrective action will have to be taken. The next section describes a set of alternative possibilities.

2.4 ALTERNATIVE CORRECTIVE ACTIONS FOR INADEQUATE BLOCK LENGTH

2.4.1 Introduction

As described in preceeding sections, it is assumed that all potential high speed passenger corridors will have an automatic block signaling system currently installed, with block spacing and signal aspects suitable, in most cases, for 125 MPH operation, but not for 150 MPH operation. For those corridors that require signal system modification, various options are available. This section suggests options to be considered. Only the block signaling system is considered; train control is discussed in the following section.

As part of this study a literature search covering foreign techniques and policies was carried out. The following discussion draws upon that activity.

2.4.2 Operating Within the Existing Block Signaling System

The British Railway System (BR) is especially interesting because the overall rail system in Britain is more nearly similar to that in the United States than any other European or Asian country. For the 125 MPH High Speed Train (HST) the British have decided to operate within the existing signal system, rather than increase either the block spacing or number of signal aspects. On all mainline sections of track BR uses a four-aspect automatic block signaling system with a standard block spacing of 3,345 feet on level, tangent track. Mainline trackage carries high density traffic consisting of a mix of conventional passenger trains with a maximum speed limit of 100 MPH and freight trains with a maximum speed limit of 60 MPH. The signaling system consists of d.c.

track circuits and pole lines, with some interlockings. For all mainline trackage, BR also uses a two-aspect, intermittent, in-cab auditory warning system.

Initially, the Signaling Department at BR expressed reservations concerning 125 MPH operation without the use of continuous cab signaling, particularly with respect to crew burden under adverse conditions. However, the management at BR felt this was not economically justifiable. (The Signaling Department did not object to the speed limit in terms of aspects or signal spacing.) BR, for HSPT, assumes a worst case adhesion limit of 2.0 MPH/Sec. for 0 to 125 MPH, and therefore assumes that the 125 MPH train can always be stopped in less than 6,000 feet, or in approximately 90% of the available distance.[9]

2.4.3 Providing an Additional Signal Aspect

If, for a particular corridor, the maximum speed possible with the existing block spacing is deemed insufficient, the most desirable approach is likely to be use of an additional signal aspect. This approach would be relatively inexpensive – on the order of $2,000 per track, per mile – and would have the advantage of not increasing headways. Thus line capacities would not be reduced when HSPT's are not involved, as would result from use of longer blocks. In addition, this approach would provide sufficient stopping distances at near-minimum headways when HSPT's are involved. The additional aspect would be ignored (i.e., considered to be the same as a "line clear" indication) by all trains other than HSPT's.

Adding an additional signal aspect is an approach used by the French on many high speed routes. Over the past ten years, speeds on the SNCF (French National Railway) have been increased to 100 MPH. Sufficient stopping distances were maintained by increasing braking power and by relocating distant signals. However, in 1968 SNCF decided to attempt to increase speed limits, first to

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[9] H.P. Roberts, "Improved Braking Raises BR's Inter-City Speeds," Railway Gazette International, February 1973; J.F.H. Tyler, Railway Division Journal, Institution of Mechanical Engineers, V1, pt. 3, 1970.

125 MPH and then 150 MPH, with the eventual long term objective of operation of a few lines at 200 MPH. SNCF felt that, with the exception of both high density and very high speed lines, the high cost of complete line signal reorganization was not justified.[10] In searching for a less costly solution for those lines not meeting the reorganization criteria, SNCF decided to add an additional signal aspect — flashing green — which would be applicable only to HSPT's. The additional-aspect signal system is now in operation on the SNCF for trains with a speed limit of 125 MPH.[11]

The SNCF rail system is somewhat diverse, but the sections of interest here are mainline track servicing both freight and conventional passenger trains. Either three or four-aspect automatic block signaling systems, with interlockings, are used. The allowed braking distances are about 4,800 feet, implying minimum block lengths of 4,800 feet for three-aspect signaling systems, and 2,500 feet for four-aspect systems, on level track. On these lines SNCF also uses a two-aspect, in-cab warning system, The warning system is mechanical in design and uses a "crocodile ramp" actuator, located between the rails just in advance of the wayside signal mast, which conveys mechanically to the locomotive cab whether or not a restrictive signal is about to be passed. If a locomotive passes a restrictive signal and there is no acknowledgement by the engineman or brake application, the train's brakes are automatically applied.

To add the additional aspect, SNCF uses an audio frequency a.c. pole line overlay transmit/receive system which transmits the status of each wayside signal back to the next wayside signal. (Actually, to add an additional aspect to a three-aspect system, the overlay is not necessary, as the information could be carried through the polarity of the d.c. signal.) For those lines operated

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[10] J. Michaux and M. Laplaiche, "Braking and Signaling Problems Arising with High Speed Trains," Proceedings of IRCA-UTC "High Speeds" Symposium, Section II, p. 390, Vienna, 1968.

[11] "SNCF Adds a Signal Aspect for High Speed Trains," Railway Gazette International, April 17, 1970.

with a speed limit of 125 MPH, SNCF also removed the mechanical "crocodile ramp" warning system and installed either a four- or five aspect intermittent cab signaling system, using inductive transmitting and receiving loops.

This is an interesting approach; hardware and installation costs are held to a minimum, and substantial benefits are accrued, especially in terms of the problem of interference between slower moving freight trains and high speed passenger trains. The hardware and technology is proven, and consists essentially of off-the-shelf items. While flashing green may not be the ideal aspect to add, the concept of providing an additional aspect is a viable and economical approach.

2.4.4 Manual Blocking

During demonstration or consumer acceptance operations in those cases where the maximum speed possible with the existing block length is deemed unacceptable, it has been suggested that a manual block system be used. Not only does this approach compromise safety — dispatchers are not infallible — but also the traffic densities and existing line capacities involved tend to make this approach impractical. Line capacity is, roughly speaking, inversely proportional to block spacing. If the manually controlled block lengths are kept short — on the order of 2 to 5 miles — the high labor costs associated with adding additional dispatchers will almost certainly be unacceptable. If the block lengths are increased to 20 miles or so, the reduction in line capacity is also quite likely to prove unacceptable. The changeover from a three-aspect automatic block signaling system with a block spacing of 9,000 feet to a manual block system with a block spacing of 16 miles reduces capacity by about 80%.

3. TRAIN CONTROL SYSTEMS

3.1 INTRODUCTION

The signal system previously discussed provides block occupancy information necessary to safe movement of trains. The typical automatic block signal system is based upon display of this information on wayside signals. This section deals with means of providing such information within the locomotive cab and of bypassing the engineer under certain circumstances. The various methods of accomplishing these additional functions are commonly characterized as "train control systems."

The engineman's responsibilities while operating a train are complex, the degree of complexity increasing disproportionately with higher speed. He is essentially deluged with information, all of which he must accurately receive, understand, assimilate, and act upon. In addition to receiving information about the locomotive's operating equipment, he must also observe signal indications, station stop information, grade markers, whistle boards, mileposts and other position landmarks. These activities are in addition to the fundamental task of obstacle detection through visual inspection of the track ahead. All of these inputs are necessary pieces of information; all are vital for safe operation. Total dependence upon visual detection of wayside block signals, even with adequate block spacing, would raise severe questions of safety. Note that at 120 MPH a sight distance of 1/4-mile would allow only 8 seconds for determination of the aspect. Thus, a variety of means of supplementing the crew sensing capabilities with automatic devices have been developed and implemented.

Federal regulations currently restrict both freight and passenger train speeds to below 80 MPH unless both the lead locomotive and the district are equipped with a compatable train control system.[12] "Train control systems," for these purposes may be described in terms of five general classifications.[13] They are:

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[12] Code of Federal Regulations, Title 49, Part 236.567 (1974).

[13] Within each of the five general classifications there are a number of variances, and in addition, the names of each of the classifications are not universally accepted. One of the signal supply companies refers to Automatic Train Protection (ATP) rather than Automatic Train Stop. The two, however, convey the same meaning.

1. Automatic Cab Signaling Systems – intermittent (ACS)i
2. Automatic Cab Signaling Systems – continuous (ACS)c
3. Automatic Train Stop Systems – intermittent (ATS)i
4. Automatic Train Stop Systems - continuous (ATS)c
5. Automatic Speed Control Systems (ASC)

3.2 AUTOMATIC CAB SIGNALING SYSTEMS - INTERMITTENT (ACS)i

Intermittent cab signaling systems are the least expensive and offer the least protection of any form of train control equipment. With this system, wayside signal aspects are repeated and displayed in the cab. However, the in-cab aspects are not updated continuously but rather, intermittently, at the entrance to each block. Intermittent systems are almost invariably installed as an addition to an existing block signaling system. Completely new signaling instalations – new block signaling as well as new cab signaling - generally involve continuous rather than intermittent systems.

Intermittent systems in the United States operate on the principle of electromagnetic coupling between a wayside transmitter and a locomotive mounted receiver.[14] The system is comprised of four major elements:

1. A transmitting loop or coil of wire usually buried between the rails and located just in advance of the entrance to the corresponding block.
2. A locomotive-mounted receiving loop or coil.
3. A device, usually a permanent magnet, located just in advance of the transmitting loop, designed to cancel the old indication just before the new aspect is registered.[15]

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[14] Early cab signaling systems did use mechanical devices to transmit the signal indication from the wayside to locomotive. Some Systems in Europe and Asia still use mechanical actuators.

[15] Often elements 2 and 3 are combined by wrapping a coil of wire around a permanent U-shaped magnet.

4. A display panel and audio announcer mounted inside on the locomotive cab.

Federal regulations consider cab signaling systems, both continuous and intermittent, to be in the same general class as train control systems. Cab signaling systems are, therefore, subject to the same rules, standards, and instructions and therefore offer compliance with the 79 MPH rule, etc. The only function of both intermittent and continuous cab signaling systems is that of providing information to the engineman. The display panel "remembers" the indication of the last wayside signal. It is a Federal requirement of all cab signaling systems that an audible warning be issued to the engineman, in the event that the on-board cab signaling equipment detects a change from a less restrictive to a more restrictive signal aspect. It should be pointed out, however, that with cab signaling alone, failure of the engineman to respond to the audible warning <u>does</u> <u>not</u> result in an automatic brake application or in any other automatic corrective action.

The other principal disadvantage of intermittent cab signaling systems is that the panel always displays the indication of the last signal that the locomotive passed. The engineman does not have the advantage of being able to "feel ahead." He is not immediately notified of changing conditions. Thrown switches, rock slides, and trains reversing direction all would present potential hazards where safety is dependent on the timeliness of the engineman's response. The long block lengths common in the United States tend to decrease the effectiveness of intermittent systems. While a few intermittent cab signaling and intermittent train stop systems are currently in use in the United States, most installations within the past forty years have been overseas. The shorter block lengths of Asian and European systems are somewhat more adaptable to intermittent systems.

The cost of adding intermittent cab signaling to an already existing automatic block signaling system would be approximately

$3,000 per track-mile plus an additional expenditure of approximately $8,000 per locomotive.[16]

3.3 AUTOMATIC CAB SIGNALING SYSTEMS - CONTINUOUS (ACS)c

Continuous cab signaling systems are similar to intermittent systems except that coded (modulated) track circuits are used, rather than inductive loops, to relay the information from the wayside to the locomotive. This system has the advantage of providing the engineman with continuously updated information concerning the status of the next approaching signal. This capability, which enables the engineman to "feel ahead," is a significant improvement over intermittent systems.

Most of the existing automatic block signaling systems in the United States are either three- or four-block systems. In the event of rapidly changing conditions a sufficient stopping distance may not remain if the information is not relayed to the engineman until the locomotive reaches the next signal. There are definite benefits to be derived from advance notice of signals ahead. Increased operating efficiencies can accrue in allowing a long freight train or high speed passenger train to resume speed, knowing that the track ahead has just recently been cleared.

In most installations, an a.c. coded signal is superimposed over the d.c. track signal. The d.c. track circuit is used for train detection. The coded a.c. signal is used to transmit signal indications to the locomotive and, in some installations, to activate the wayside signals. The use of coded track circuits does, therefore, improve the degree of "failsafe" protection, in the sense that the d.c. signal must be first detected before the a.c. signal can be transmitted and detected at the other end of the track.

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[16] This and the other cost estimates in this section should be considered rough estimates for an "average" railroad environment which does not have extremes in switching complications, noisy track circuits, grade crossings, etc., in 1974. Accurate cost estimates can only be prepared after considering a specific system on a specific section of a specific railroad.

The approximate cost of adding a continuous automatic cab signaling system to an already existing automatic block signaling system would be approximately $30,000 per track-mile plus $8,000 per locomotive.

Cab signaling systems also form the basis for Automatic Train Stop and Automatic Speed Control systems. The basic limitation of cab signaling systems is that, although additional information is supplied to the engineman, the system still relies upon him to take the appropriate action.

As of January 1, 1973, there were 2,855 miles of automatic cab signaling installed in the United States, and 3,143 miles of either automatic train stop or automatic speed control.[17] Thus less than 3% of the railroad mileage in the United States is equipped with any form of train control or cab signaling systems. As of that same date, approximately 5,420 locomotives and multiple unit self-propelled (MU) passenger cars were equipped to accept either cab signals, Automatic Speed Control, or Automatic Train Stop.

3.4 AUTOMATIC TRAIN STOP SYSTEMS (ATS)

Automatic Train Stop systems are direct extensions of cab signaling systems; the primary difference is that if the engineman does not acknowledge the passage of a restrictive signal aspect, the ATS system will automatically initiate an emergency brake application. Once this "penalty" emergency brake application begins, there is no means by which the engineman can cancel it and prevent the train from coming to a full stop. As with intermittent ACS systems, intermittent ATS systems control the train only at specific discrete points (at the entrance to each block) through the use of inductive transmitting and receiving loops. With continuous systems, control is applied continuously, through the use of coded AC track circuits.

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[17] Unpublished Statistics compiled by the Federal Railroad Administration, Office of Safety, January 1, 1973.

There is considerable variation in the types and operation of ATS systems presently in use in the United States. Some systems do not provide a visual display of the signal aspects in the locomotive. ATS systems, while protecting the engineman from gross violations (i.e., disobeying a signal), allows him to use his skill in operating the train. The principle weakness of all ATS systems is that the control is lacking in finesse – it has only two states: full stop, or any speed that the engineman wishes.

As of January 1, 1973, there were 2,370 road miles of ATS systems installed on Class I railroads in the United States, most of which were intermittent systems. As of that same date, there were approximately 1,000 locomotives and MU cars suitably equipped. Approximately 1% of all the road mileage and approximately 5% of all the road-service locomotives and MU cars have been equipped for Automatic Train Stop systems.

The approximate cost of adding an intermittent ATS system to an existing block signaling system would be $3,000 per track-mile plus $8,000 per locomotive.[18] For a continuous system, the cost per locomotive would be the same and the cost per track-mile would be approximately $30,000.

3.5 AUTOMATIC SPEED CONTROL SYSTEMS (ASC)

The last and most elaborate form of automated train control to be considered here is Automatic Speed Control (ASC). All ASC systems are built around continuous Automatic Train Stop systems with the addition of an on-board computer-driven servo system. The servo system enforces speed limits by tapering the velocity down to an acceptable level after the locomotive passes a restrictive signal, while going around curves, or through interlockings, station areas, etc. In the event that the locomotive passes a restrictive signal aspect and the engineman does not respond by applying the brakes or acknowledging the aspect, the on-board

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[18] The cost figure quoted here to equip a locomotive suitable for ATS includes the cost to include a cab signaling display panel. Also see Improved Passenger Service for the Northeast Corridor, Op. Cit; Improved Passenger Service for Three Corridors, Op. Cit.

computer, which keeps track of the locomotive's speed and position within the block, adjusts the train's speed accordingly.

These systems are by their very nature continuous systems, and, as a result of the on-board computer-driven servo system, offer a much more refined (or gradual) form of control than do continuous ATS systems. ASC systems have proven to be extremely effective in the prevention of collisions and derailments resulting from overspeed conditions. In addition, the system allows the engineman to "feel ahead" to react to rapidly changing conditions and also offers fairly complete protection against the possibility of a gross error in judgment or perception by the engineman.

A distinction is commonly drawn between automatic train control (ATC), which provides only for overspeed protection, and automatic train operation (ATO), in which speed can be both increased and decreased to meet a specified velocity profile, consistent with block occupancy conditions.

The costs involved in upgrading an Automatic Block Signaling system to include an ASC capability would be approximately $30,000 per track-mile and $15,000 per locomotive.

As of January 1, 1973, 640 miles of Class I railroad line were equipped with Automatic Speed Control equipment and 490 locomotives were equipped for ASC. That is, less than .3 per cent of the trackage and less than 2 per cent of locomotives were equipped for Automatic Speed Control. Full ATO has been used only in a few specialized ore-train and rapid transit applications.

3.6 CENTRALIZED TRAFFIC CONTROL (CTC)

Centralized Traffic Control, generally known as "CTC," is not a train control system in the sense defined previously in this section, but will be described here for completeness. CTC is, as the name implies, a means for controlling traffic and not a safety system for preventing collisions. In essense, it is a system in which a dispatcher has the means to control and direct traffic over a portion of the railroad by remotely changing block signals and switches. The dispatcher receives a continuous indication of block occupancy (determined by track circuits) and "sets up" a route for any particular train through electrical circuits which control signals and track switches. Varying degrees of automation are possible in this process. However, system safety resides within the basic signal system upon which CTC is imposed: should a dispatcher attempt to set up an unsafe condtion (throw a switch in front of an on-coming train or give one train a signal allowing entry at unrestricted speed into an occupied block), the basic signal system would ignore these commands. The CTC dispatcher can never provide a less restrictive indication than that permitted by the automotic block signal system.

The major benefit of CTC is efficient operation, particularly in high traffic areas or through complex track configurations. The experienced dispatcher chooses routes and assigns priorities in a manner which minimizes delays and conflicts. (Note that the signal system per se merely prevents collisions, and in complex configurations could easily generate the safe but undesirable condition of all trains at a standstill.) CTC can thus permit much greater traffic capacity then would otherwise be the case, particularly in operating traffic in both directions when trains frequently must either go into a siding or to a passing track. CTC is commonly installed as traffic in single track territory approaches 40 trains per day. Modern installations can permit control of more than 1000 miles of railroad from one dispatching room. ("Centralized Traffic Control," Bulletin No. 176 of the Union Switch and Signal Division, Westinghouse Air Brake Co., provides a detailed description of the workings of a variety of CTC applications.)

4. SAFETY IMPLICATIONS OF TRAIN CONTROL SYSTEMS

4.1 INTRODUCTION

Consideration of the role of automated train control devices and systems requires examination of the potential benefits and the effectiveness of each type of system. This section addresses the ability of train control devices to prevent accidents which result from conditions applicable to operation of high speed passenger trains. Predictive accident-rate calculations will be developed for Automatic Block Signaling Systems and then for each of the train control systems described in Section 3. The primary source of data to be used for this analysis is the Summary of Accidents Investigated, published by the Office of Safety of the Federal Railroad Administration for the fiscal years 1970, 1971 and 1972.

4.2 METHODOLOGY

In the past, studies have been conducted for the Federal Railroad Administration and others to determine the causal factors in railroad accidents.[19] In addition, a general study of train control devices and their potential effectiveness was completed for FRA in 1969.[20]

The primary source of accident data for those reports has always been the Accident Bulletin.[21] The Bulletin lists the number

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[19] Rail Safety Research Plan for the Fiscal Years 1971 - 1975, R.E. Morris and J.A. Richardson, DOT Report No. DOT-FR-9-0047, October 1969; "Signals and Operating Rules as Causal Factors in Train Accidents," NTSB Special Study, NTSB Report Number: NTSB-RSS-71-3, February 1972.

[20] Study carried out for FRA by Walter P. Quintin, Jr., consultant.

[21] Accident Bulletin, published each year by the Office of Safety, Federal Railroad Administration, Department of Transportation

of deaths and injuries caused by train accidents each year, categorized by the class of person injured and the primary causes of the accident.

The Bulletin does not, however, give a further breakdown of accident location (i.e., within yard limits or on a main or branch line); the signaling system in operation at the time (i.e., manual block, automatic block, ATS, none, etc.); or the types of trains involved (i.e., freight or passenger). Moreover, in the event that — as is often the case — an accident resulted from multiple causes, the Bulletin will only show the direct cause of the accident. Some accidents, while not caused by either a signal system failure or negligence of employees, might very well have been preventable by some form of automatic train control — for example, an accident caused by malicious tampering with a switch when an approaching train is within the same block as the switch might very well have been prevented, or the severity lessened, by a continuous ATS system. Lastly, most of the information that the Office of Safety uses to generate the Bulletin is supplied by the railroad on which the accident occurred; a formal, objective investigation is generally carried out only when fatalities or extensive property damage result.

Since those previous studies were prepared, a new source of data has become available. Each year the Federal Railroad Administration investigates approximately 120 serious railroad accidents. The FRA publishes a few of the original accident reports and now also publishes one report containing a summary of each of the 120 final accident reports.[22] Use of the accident summary report, supplemented by the Bulletin, would appear to solve most of the problems associated with using just the Bulletin, as the summaries are detailed and not aggregated. That approach has been followed here.

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[22] Summary of Accidents Investigated in the Fiscal Year 1969 - 1970, 1970 - 1971, and 1971 - 1972, U.S. Department of Transportation. Federal Railroad Administration.

Two calendar years were selected for the analysis, 1970 and 1971.[23] Figure 4-1 shows a plot of the number of train-train collisions and derailments which resulted in casualties, the number of train miles, and the total number of casualties resulting from train-train collisions and resulting from derailments for the years 1968-1973. As can be seen from the plots, calendar years 1970 and 1971 appear to be typical years in terms of railroad accidents and casualties.

4.3 ACCIDENT RATE CALCULATIONS - HISTORICAL

An examination of the accident summaries for 1970 reveals that the FRA investigated 38 train-train collisions resulting in casualties. These 38 collisions resulted in 22 deaths and 249 injuries[24] In addition, the examination indicates that, of the 38 collisions, 19 were accidents which resulted from conditions applicable to the operation of high speed passenger trains. Accidents which occured in nonsignaled territory and resulted from a disregard of train orders or the time table, accidents caused by shifting or exploding lading, accidents which took place within yard limits, etc., are not considered to have resulted from conditions applicable to high speed passenger trains, and were therefore

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[23] Only two complete calendar years of dates are currently available. A Summary Report on 240 accidents is not a statistically perfect sample, but allows useful insight into the problem.

[24] The FRA uses a slightly different criteria for reporting in the Bulletin than is used for the Accident Reports. Therefore. the numbers listed in the Bulletin may not always correlate one for one with the Accident Investigation Reports. However, judging from the magnitude of the number of casualties resulting from train-train collisions reported in the Bulletin versus the number from the Accident Investigation Summaries, it would seem fairly certain that the FRA does investigate all of those accidents which cause almost 100 percent of the casualties.

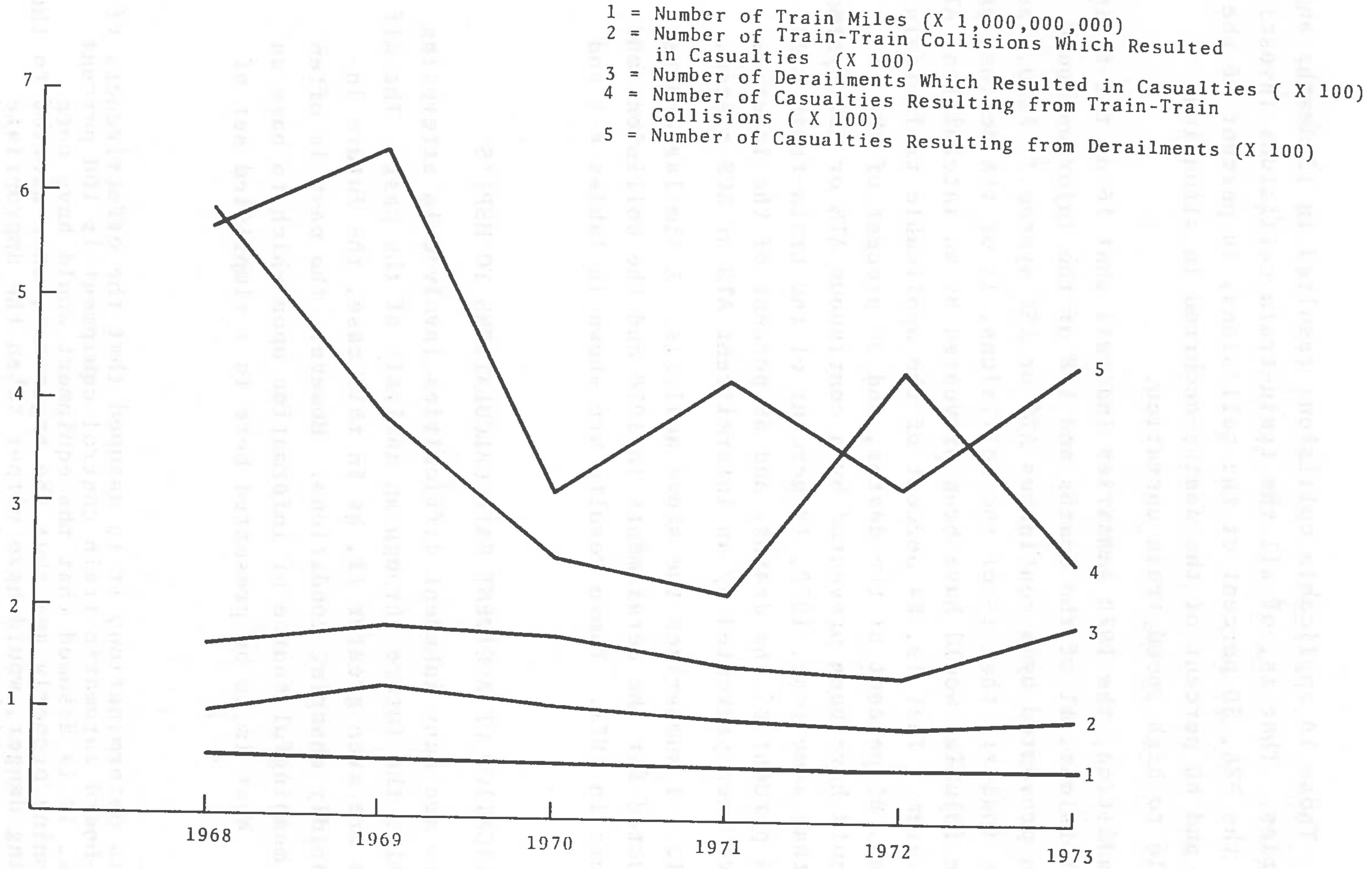

Figure 4-1. Historical Accident Trends

omitted. Those 19 applicable collisions resulted in 13 deaths and 198 injuries. That is, of all the train-train collisions investigated by the FRA, 50 percent of the collisions, 80 percent of the injuries and 60 percent of the deaths occurred in situations applicable to high speed train operation.

In addition, the 1970 summaries indicate that 16 of the train-train collisions, 11 of the deaths and 178 of the injuries would have been prevented by a continuous ATS or ASC system.[25] Also, the summaries indicate that 15 of the collisions, 11 of the deaths, and 59 of the injuries would have been prevented by an intermittent ATS or ASC system. That is, 84 percent of the applicable train-train collisions, 85 percent of the deaths, and 90 precent of the injuries would have been prevented by a continuous ATS or ASC system; and for that same year, 1970, 78 percent of the train-train collisions, 85 percent of the deaths, and 30 percent of the injuries would have been prevented by an intermittent ATS or ACS system.

Table 4-1 summarizes the above analysis. A similar analysis was conducted for the derailments in 1970 and the collisions and derailments in 1971. Those results are shown in Tables 4-1 and 4-2.

4.4 APPLICATION OF ACCIDENT RATE CALCULATIONS TO HSPT'S

There are many inherent difficulties involved in attempting to determine the future through an analysis of the past. The difficulties are even greater if, as in this case, the future involves rapidly changing conditions. However, the past is often the only meaningful source of information upon which to base an estimate. What is to be presented here is a simplified set of

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[25] For this determination, it is assumed that the effectiveness of any on-board automatic train control equipment is 100 percent. That is, it is assumed that the equipment would have been functioning properly and that the engineman, once alerted to the impending danger, would have either taken the appropriate action, or would have ignored the warning completely. If a warning is ignored on ATS or ASC systems, the brakes are automatically applied and power is removed.

TABLE 4-1. COLLISIONS AND DERAILMENTS, 1970

	Investigated by FRA	Applicable to HSPT Operation		Preventable by ATS(c) or ASC		Preventable by ATS(i) or ACS	
		number	%	number	%	number	%
Collisions Which Resulted in Casualties (Train-train)	38	19	50	16	84	15	79
Deaths Which Resulted from Train-Train Collisions	22	13	59	11	85	11	85
Injuries Which Resulted from Train-Train Collisions	249	198	80	178	90	59	30
Derailments Which Resulted in Casualties	17	13	76	2	15	1	8
Deaths Which Resulted from Derailments	8	6	75	0	0	0	0
Injuries Which Resulted from Derailments	81	68	84	6	9	2	3

TABLE 4-2. COLLISIONS AND DERAILMENTS, 1971

	Investigated by FRA	Applicable to HSPT Operation		Preventable by ATS(c) or ASC		Preventable by ATS(i) or ACS	
		number	%	number	%	number	%
Collisions Which Resulted in Casualties (Train-Train)	37	17	46	14	82	13	76
Deaths Which Resulted from Train-Train Collisions	25	6	24	6	100	4	67
Injuries Which Resulted from Train-Train Collisions	211	94	45	85	90	83	88
Derailments Which Resulted in Casualties	21	17	81	2	12	0	0
Deaths Which Resulted from Derailments	4	3	75	2	67	0	0
Injuries Which Resulted from Derailments	205	133	65	4	3	0	0

calculations, based upon the past history of rail accidents, designed to permit estimation of the need for and potential benefits of train control systems.

4.4.1 Comparison of Accident Rates for Passenger and Freight Trains

From Tables 4-1 and 4-2 and from Figure 4-1, it is apparent that the historical rate of serious train-train collisions resulting from conditions applicable to HSPT's is approximately 3.5 collisions per 100,000,000 train miles.

That historical accident rate of 3.5 collisions per 100,000,000 train miles is, of course, very heavily based on the record of freight trains.[26] It is believed by some that train crews and railroad operations in general are more safety conscious and less prone to neglegence (and accidents) in passenger service. That theory would indicate that the rate of 3.5 collision per 100,000,000 train miles is higher than is really appropriate. However, the accident data for 1970 and 1971 tend to refute the contention that passenger trains are less prone to conditions which cause train-train collisions. The rate for passenger trains for 1970 and for 1971 was approximately 4.0 collisions per 100,000,000 train miles. It should be pointed out that of the six serious, applicable train-train collisions involving passenger trains in 1970 and 1971, two resulted from negligence of train crews and three would have been prevented by some form of automatic train control. Not all accidents which are train-control preventable result from negligence of the crew of the passenger train.

4.4.2 Aggregated Train Miles

The annual number of train miles is a composite of train miles accumulated in time table and train order territories and automatic train control and cab signaling territories. The listing of HSPT-

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[26] For the years 1970 and 1971 freight trains accounted for approximately 86 percent of the total train miles.

applicable train-train collisions does not include accidents which occurred in time table and train order territory, so the accident rate shown might be an underestimation. However, since over 50 percent of the route mileage in the United States has an automatic block signaling system installed, and the installation has tended to be on high and medium density lines, it seems fair to assume that a very small percent of the train miles were actually accumulated on other than automatic block signaling systems.

4.4.3 Accident Rate Calculations

Consider a hypothetical corridor, characterized by the following parameters

Length: 200 miles

Passenger Train Density: 50 trains per day

Freight Train Density: 60 trains per day

Passenger Train Capacity: 300 seats

Passenger Train Load Factor: 50%

Probability of a Collision: 4/100,000,000 train-miles

Such a system would record a total passenger traffic of 550 million passenger miles per year; these numbers are in reasonable accord with proposed actual corridors and agree with Amtrak's present schedule between New York and Washington. In recent years the fatality rate associated with scheduled domestic air carriers, buses, and rail service has been on the order of 0.2 deaths per hundred-million passenger-miles. Applied to the corridor described above, that rate would imply 1.1 fatalities per year.

From the previous section it seems reasonable in the corridor without any form of train control to assume an accident rate of 4 train-train collisions per 100,000,000 train-miles. Assuming that a train-train collision results in 75 deaths – admittedly a very approximate but not unreasonable assumption, considering the speeds involved – the hypothetical corridor defined above would result in 0.15 collisions per year or 11 deaths per year. That accident rate would imply a system fatality rate 10 times greater than now found in public intercity transportation. In addition, this assumes no deaths from any other source, such as grade crossing derailments or collisions.

If the same corridor is considered with the addition of an Automatic Speed Control system, Tables 4-1 and 4-2 would indicate a collision probability on the order of 0.4 train-train collisions per 100,000,000 train-miles. This would result in a fatality record for this hypothetical corridor of 1.1 fatalities per year, or .2 deaths per 100,000,000 passenger-miles. Over a 10 year period this would result in a potential savings of approximately 100 lives, and would approximately match the safety of other modes.

However, the costs of upgrading such a corridor are substantial. In the last section, the cost to modify an Automatic Block Signaling system to include Automatic Speed Control has been estimated to be approximately $30,000 per track mile, plus $15,000 per locomotive. It is important to remember that not only the lead locomotive of passenger trains, but also the lead locomotive for all freight trains operating in the corridor must be equipped if the system is to be fully effective. Assuming that the corridor is a two-track line, and that 50 passenger trains and 100 freight locomotives are to be equipped, the cost to up-grade such a corridor would be approximately 15 million dollars.

5. THE IMPACT OF PASSENGER TRAIN OPERATION ON FREIGHT SERVICE

5.1 INTRODUCTION

A primary function of this report is to outline the potential signaling and control problems involved in operation HSPT's in a high density rail corridor. It is therefore appropriate to consider the general operating efficiency of the line, as well as the safety of the passengers and train crews. Previous portions of this report have dealt with safety considerations. This section considers headways, track capacity and operational efficiency. More specifically, it deals with adverse affects on freight operations associated with the introduction of high speed passenger trains.

General headway formulas will be developed and a train graph analysis will be presented for a hypothetical 200 mile corridor. A sensitivity analysis of the train graph model is presented and major areas of decreased freight service efficiency will be discussed.

5.2 HEADWAY MANAGEMENT

5.2.1 Headways

In order to determine the effect on line capacity of introducing high speed traffic, one must first consider changes in headways. Maximum line capacity, for a given set of operating constraints, occurs when all trains in the system are operating at or near minimum headways.

The function of headway management is to insure that under normal operating circumstances trains never interfere with one another. That is, a following train is never forced to reduce speed and the engineman in a following train never sees a restrictive signal aspect under normal operating conditions. Maximum line capacity implies that all trains are separated by the minimum distance necessary to prevent interference. From Figure 5-1, the minimum headway (distance separation of the leading ends of successive trains) for a three-aspect signaling system, for uni-directional

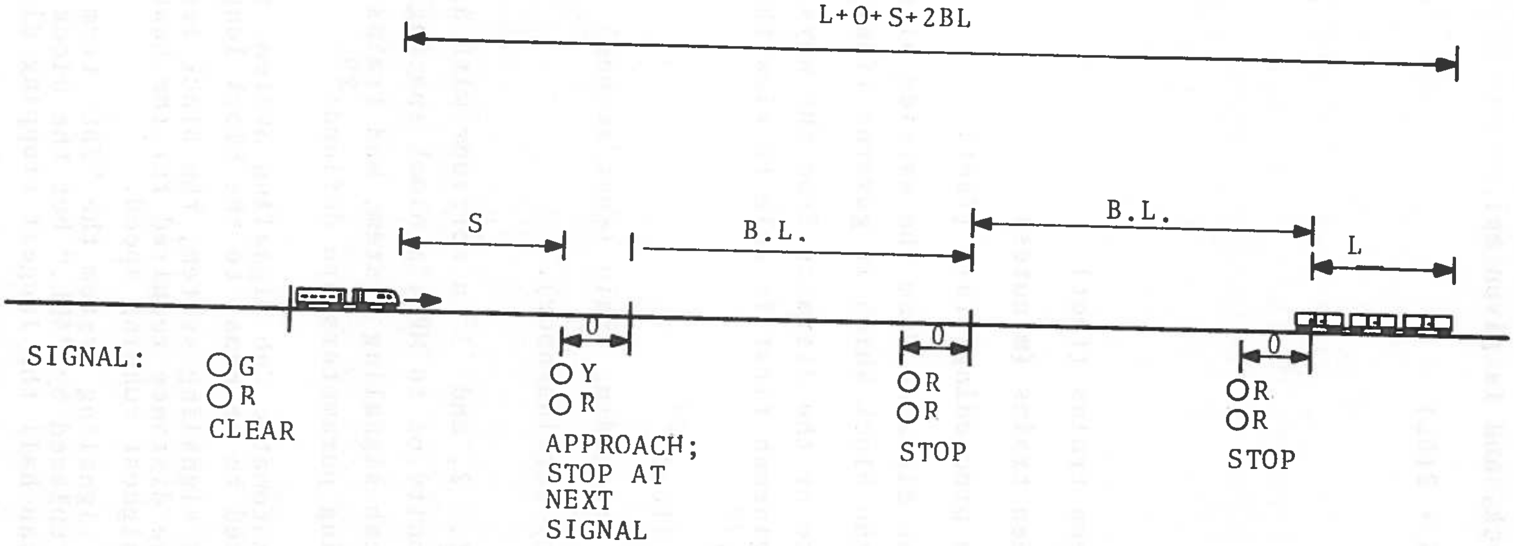

Figure 5-1. Two Trains Separated by Minimum Headway for a Three-Aspect Signal System

train movements occurs when the leading train is occupying only the last few feet of a block, and is given by:

$$h = L + O + S + 2(BL) \tag{1}$$

and,

$$H = V/(60h) \tag{2}$$

and,

$$C = 60/H \tag{3}$$

where:

h = Headway between trains (feet)

H = Headway between trains (minutes)

L = Length of the preceeding train (feet)

O = Overlap or the distance from the wayside signal to the entrance to the block which it governs (feet)

S = Sight distance or the distance from the wayside signal where the engineman first is able to view the displayed aspect (feet)[27]

BL = Block length (feet)[28]

V = Speed of the preceeding train (feet/second)

C = Track Capacity (trains/hour).

From equations 1, 2, and 3 a corridor with all trains traveling at the same velocity of 50 MPH, a block spacing of 9,000 feet, a three-aspect cab signaling system, and trains 8,000 feet in length, the following parameters are defined:[29]

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[27] For a continuous Automatic Cab Signaling System, this distance should be considered to be equal to the block length.

[28] For a three-aspect signaling system, the block length must be greater than the distance required for the heaviest train to stop from the highest running speed.

For a four-aspect signaling system the "2BL" term in equation 1 would be replaced by "3BL," but the block length need only be greater than half the longest stopping distance.

[29] For a four-aspect cab signaling system the corresponding numbers would be 5 miles, 6 minutes, and 10 trains/hour respectively, assuming a 4,500 foot block length.

$h = 6.5$ miles

$H = 8$ minutes

$C = 7.5$ trains per hour.

If, however, one attempts (as in this case) to operate trains of varying speeds with, in some cases, faster trains following slower trains, the problem is more complicated. Under those circumstances, passing tracks or sidings must be used and a more complex form of analysis must be used. In this report a train graph analysis is selected; that model is presented in the next section.

5.2.2 Train Graphs

The traditional and most easily understood method of planning train schedules and dispatching policies is through the use of a train graph analysis. Figure 5-2 shows a train graph. A train graph is a plot of time versus distance for a train on a particular section of track. The train is represented by the wide strip, with the front of the train identified with the left-most edge of the strip. The physical end of the train is indicated by the dashed parallel line somewhat to the right of the left edge. The right edge of the strip represents the end of the zone of protection which may be thought to trail behind the train.[30] In addition, the slope of the strip represents the train's velocity at any particular point in time. The Y-ordinate of the left edge of the strip represents the distance of the head end of the train from the starting point at some particular point in time, X. (A horizontal strip would represent a stopped train, and a vertical strip would represent one moving at infinite velocity.) Lastly, the vertical width of the strip represents the minimum distance-headway of the train, and the horizontal width of the strip represents the minimum time-headway of the train.

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[30] The zone of protection is, of course, equal to two block lengths plus the sighting distance, plus the overlap.

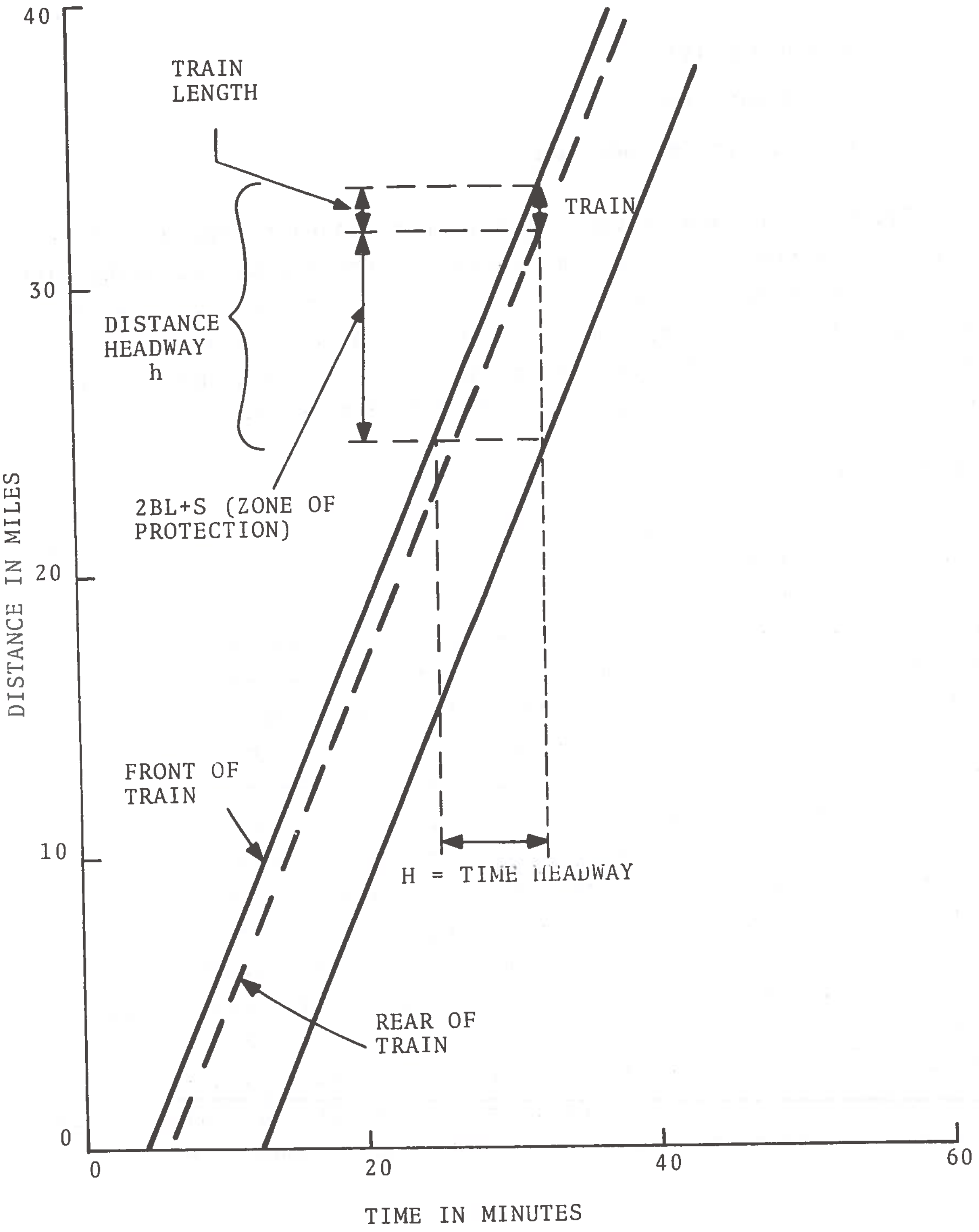

Figure 5-2. Simplified Train Graph I

Figure 5-3 shows a train graph for two potential dispatching policies, each involving a faster train following a slower train. A passing siding is shown beginning at mile post 30 and continuing to milepost 32.5, drawn as a horizontal bar, since the siding is always at the same location, independent of time. In essence, the only place that the strips which represent trains can cross safely is at a siding. In Phase I of the train graph, train A(1) is dispatched at time T = 0, at a speed of approximately 50 MPH. The alternate dispatching policy – policy #2– involves dispatching train A(2) at T = 20 minutes with a speed of approximately 35 MPH. As is seen in Phase II of the train graph of Figure 5-3, the first alternative results in train A(1) going into the siding, thus clearing the main track for train B, a 79 MPH express train which was dispatched at T = 50 minutes. The second alternative results in train A(2) interfering with, and in this case being struck by train B at mile post 12 at approximately T = 55 minutes. The second alternative is unacceptable. Phase III shows train B continuing on ahead of train A(1), and train A(1) leaving the siding and continuing on the main track.

5.2.3 Application of the Train Graph Model

The analysis which follows is dependent upon the assumptions and characterization parameters used to define the trains and hypothetical corridors. It is appropriate, therefore, to delineate those assumptions and characterizations to indicate how the assumed parameters are likely to differ from reality and to suggest the likely effects of those differences.

5.2.3.1 Signaling System – For this analysis, a three-aspect, continuous cab signaling system is assumed. The block spacing is assumed to be equal to 9,000 feet, with zero overlap distance. Because of the presence of continuous cab signaling, sighting distance is considered to be equal to block length. It is also assumed that the corridor is equipped with either Centralized Traffic Control (CTC) or Automatic Interlockings, so that power switches can be thrown in the proper sequence by remote control, in advance of train arrival.

The above assumptions concerning the signal and control system

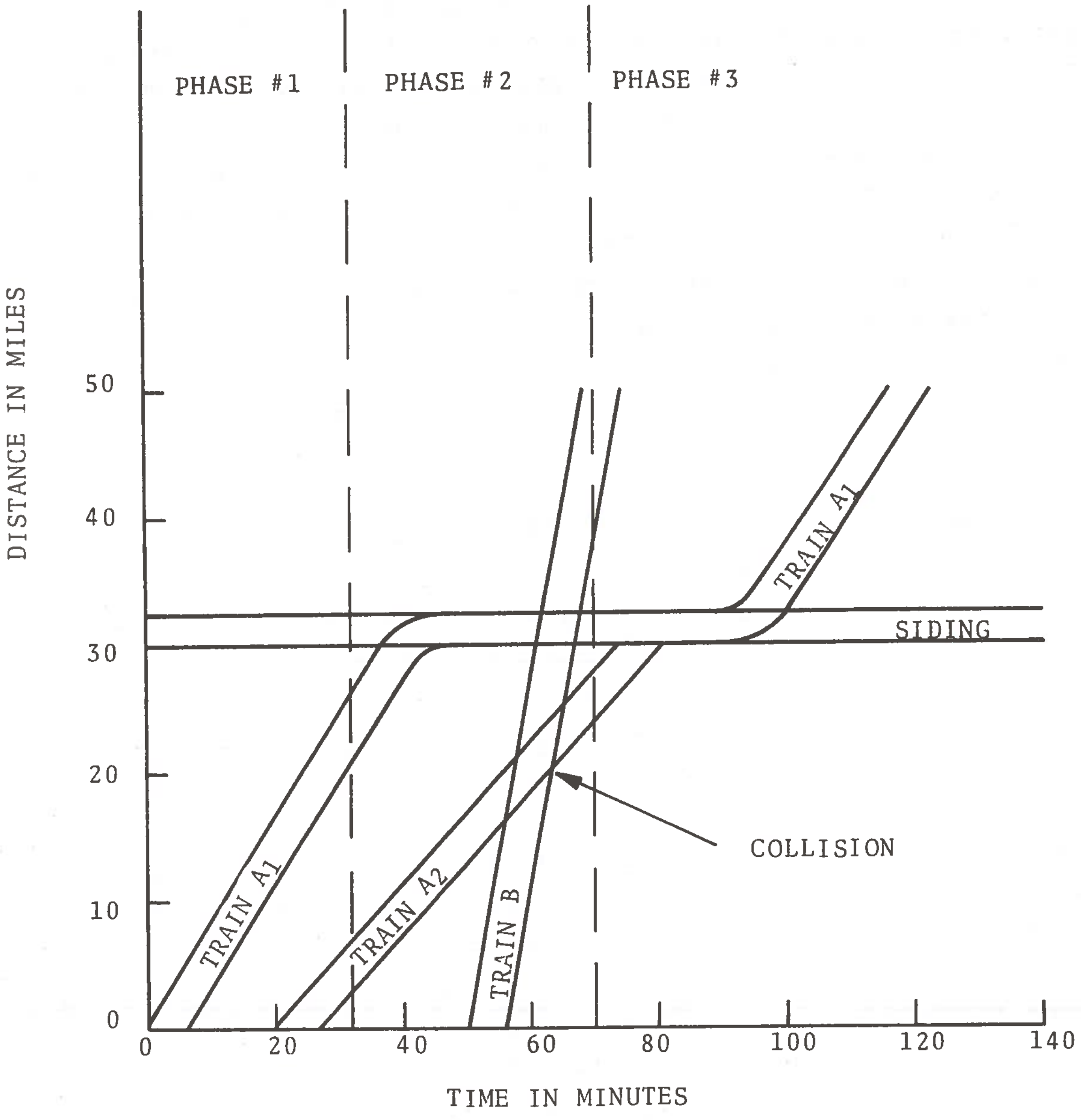

Figure 5-3. Basic Train Graph for Operation of Two Trains

are the most standard of any used in this analysis. The possible exceptions are those of slightly different block lengths or the use of a four-aspect rather than a three-aspect signal system. Neither of these changes would affect the results to any substantial degree.

5.2.3.2 Track Profiles and Train Performance – For this analysis, the hypothetical corridor is assumed to be comprised of entirely straight, level track, without grades or curves. In addition, it is assumed that all traffic consists of through or express trains that operate without switching moves or intermediate station stops.

The effect of these three assumptions is to simplify and generalize the model. Actual corridors are, of course, comprised of both ascending and descending grades, as well as level, tangent, and curved track. In the absence of accurate track profiles for any particular corridor, it is probably not worthwhile to attempt to include grades or curves. The effects of such variations on line capacity and line efficiency are, however, substantial.

Freight trains, with their low power-to-weight ratios – typically in the range of 1 to 2 horsepower per trailing ton – are severely affected by ascending grades. The top speed of a 2 HP/Ton train on a 1 percent grade is approximately 40 MPH. On the other hand, high speed passenger trains have much greater accelerating abilities – typically 7-15 horsepower per ton – and are not likely to be affected by any but the steepest grades. Thus, grades reduce line capacity by slowing freight trains.

Curves, on the other hand, will effect HSPT's much more than freight trains. Federal regulations restrict maximum train speed on curves as a function of the superelevation or track banking involved. However, even at the maximum permissible amount of banking, all trains are restricted to speeds below 113 MPH on a 1 degree (5,730 ft radius) curve, 80 MPH on a 2 degree (2,860 ft radius) curve, and 66 MPH on a 3 degree (1,910 ft radius) curve.[31] In many parts of the country, curves of between 1 and 2 degrees are common

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[31] Code of Federal Regulations, Title 49, part 213.57 (1974).

and may, in those areas, comprise 5% to 10% of the route mileage. Curves, however, will not affect line capacity as adversly as will grades, since the effect is to cause the HSPT to slow down. This effect, in and of itself, will tend to increase line capacity. Thus the problem with curves is in increasing total HSPT trip time.

5.2.3.3 Station Stops – In this analysis no attempt is made to include the effect of either HSPT station stops or freight train switching moves. The effect of HSPT station stops would be to slow the passenger train, thereby increasing line capacity. Switching moves, on the other hand, would have the effect of slowing the freight train and would thus decrease line capacity. Except for those times when HSPT's are not running, the delays caused by a switching move may be unacceptable.

5.2.4 Train Graph Analysis

5.2.4.1 Case I – Passenger Trains at 80 MPH, Freight Train at 50 MPH – This section presents the train graph model sensitivity analysis. Figure 5-4 shows a train graph of a 200 mile corridor with 80 MPH passenger trains being dispatched once every hour. Freight trains are shown traveling at a speed of 50 MPH. Sidings are shown uniformly spaced every 15 miles. The figure represents a steady-state condition. For clarity, different shadings will be used as indicated in this and in subsequent train graphs to distinguish between freight and passenger trains. The freight train graphs will be omitted in certain portions of the figures where the pattern simply repeats.

All traffic on this particular train graph is shown to be unidirectional. (A double track corridor is assumed, without crossovers.) In addition, for this graph all train meets are considered to involve a stopped train, located on a siding. In subsequent graphs running meets, passing tracks, and crossovers will be considered.

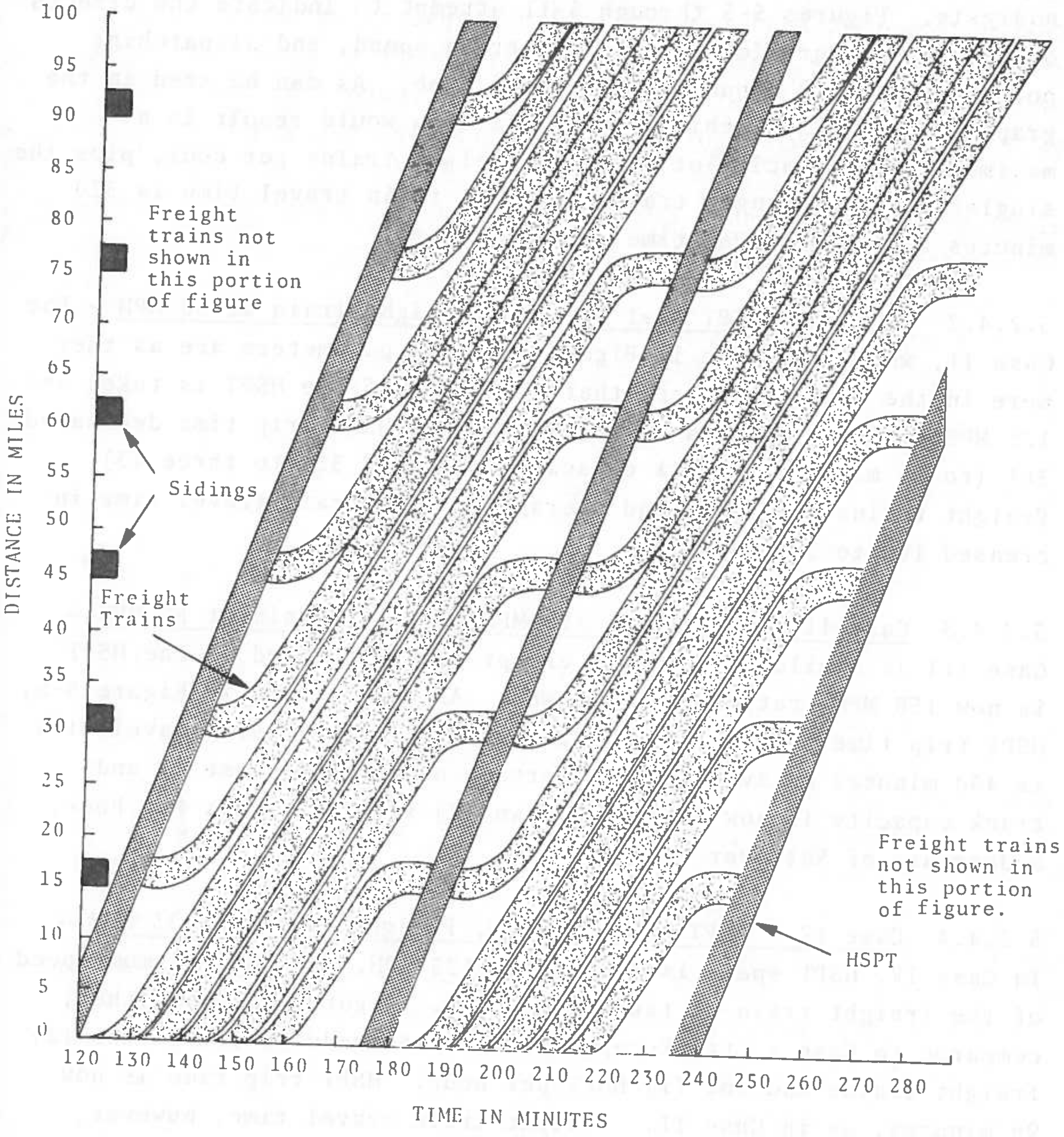

Figure 5-4. Train Graph I - Baseline Characterization (80 MPH Passenger Train, 50 MPH Freight Train)

This situation will be the baseline characterization for this analysis. Figures 5-5 through 5-11 attempt to indicate the effects of changes in corridor topography, train speed, and dispatching policies on track capacity and travel time. As can be seen in the graph of Figure 5-4, this characterization would result in a maximum track capacity of five (5) freight trains per hour, plus the single 80 MPH passenger train. Freight train travel time is 320 minutes and HSPT travel time is 150 minutes.

5.2.4.2 Case II – HSPT's at 125 MPH, Freight Train at 50 MPH – For Case II, which is shown in Figure 5-5, all parameters are as they were in the baseline except that the speed of the HSPT is taken as 125 MPH. As can be seen in the graph, the HSPT trip time decreased 36% (to 96 minutes), track capacity decreased 33% to three (3) freight trains per hour, and average freight train travel time increased 18% to 380 minutes.

5.2.4.3 Case III – HSPT's at 150 MPH, Freight Train at 50 MPH – Case III is similar to Case II except that the speed of the HSPT is now 150 MPH rather than 125 MPH. As can be seen in Figure 5-6, HSPT trip time becomes 80 minutes, while freight train travel time is 450 minutes on average, an increase of 40% over Case I, and track capacity is now limited to two (2) freight trains per hour, a decrease of 50% over Case I.

5.2.4.4 Case IV – HSPT's at 125 MPH, Freight Trains at 35 MPH – In Case IV, HSPT speed is reduced to 125 MPH, and the maximum speed of the freight train is taken as 35 MPH. Figure 5-7 shows that, compared to Case I, track capacity has been reduced 50% to two (2) freight trains and one (1) HSPT per hour. HSPT trip time is now 96 minutes, as in Case II. Freight train travel time, however, has increased to 525 minutes, an increase of 50% over Case I.

5.2.4.5 Case V – HSPT's at 125 MPH and Sidings Every 10 Miles – Case V uses the same parameters as Case II, except that passing sidings are now located every 10 miles, rather than 15. Figure 5-8 shows that HSPT trip time is unchanged at 96 minutes. Freight

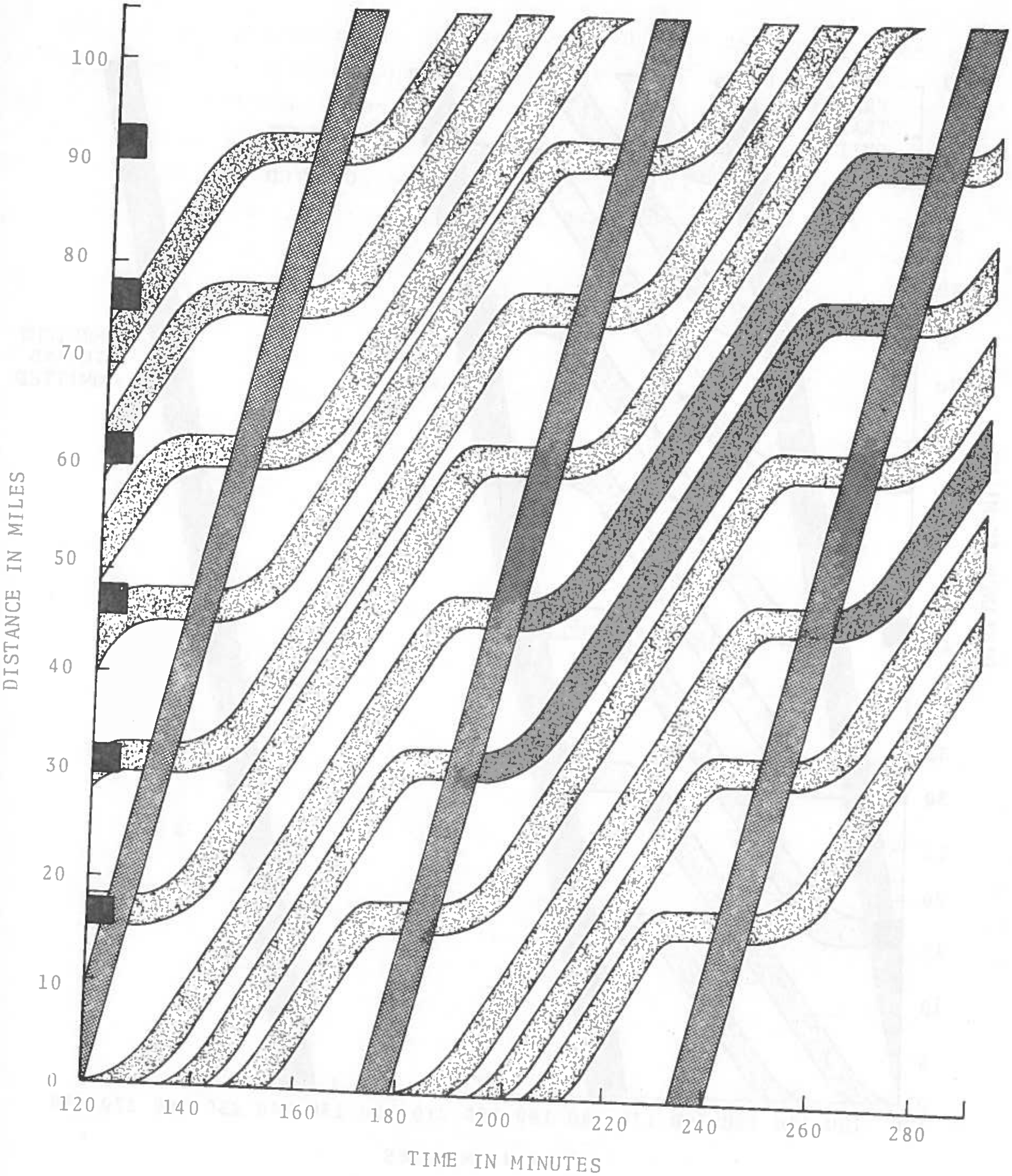

Figure 5-5. Train Graph II - 125 MPH HSPT's, 50 MPH Freight Train

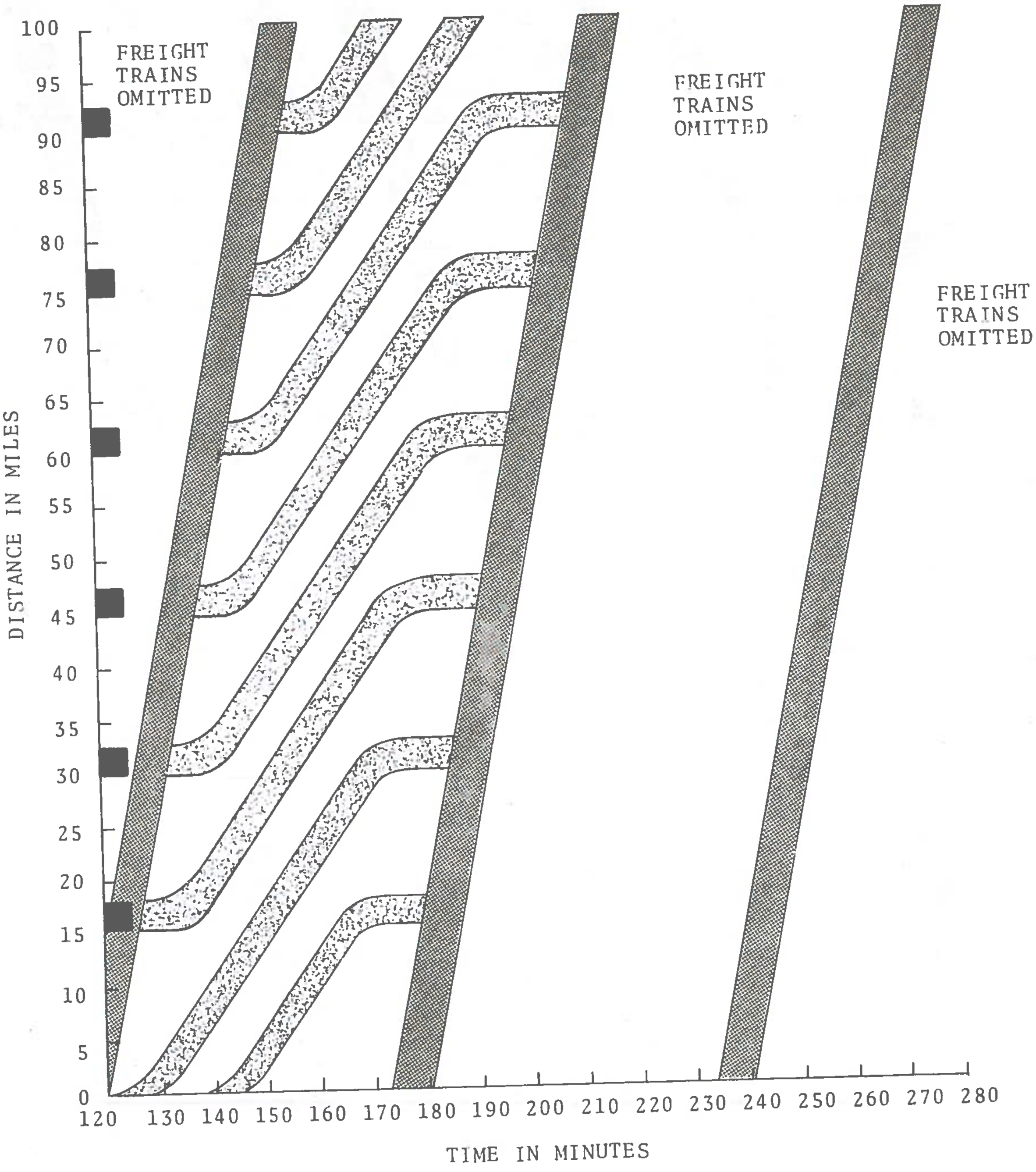

Figure 5-6. Train Graph III - 150 MPH HSPT's, 50 MPH Freight Train

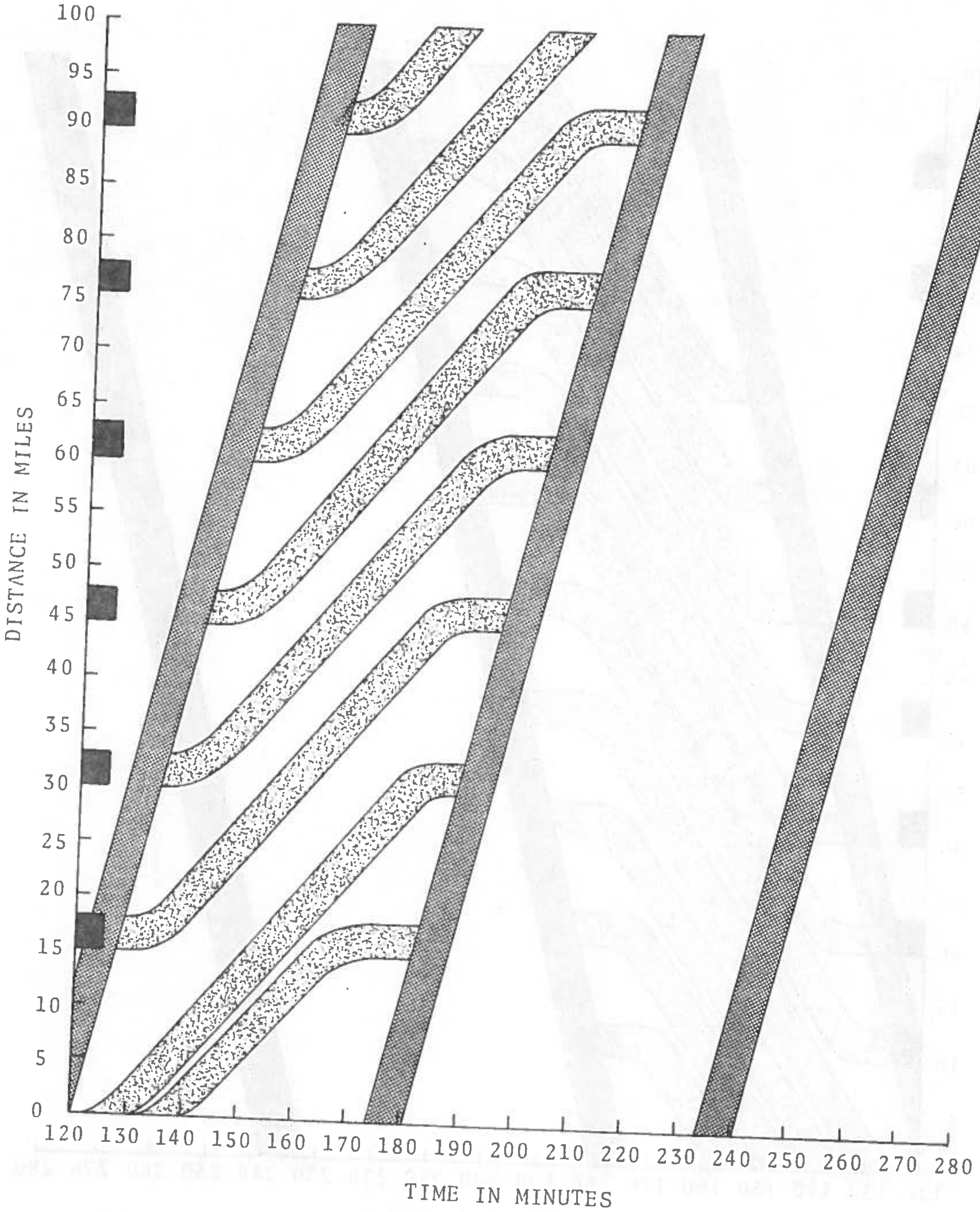

Figure 5-7. Train Graph IV - HSPT's at 125 MPH, Freight Trains at 35 MPH

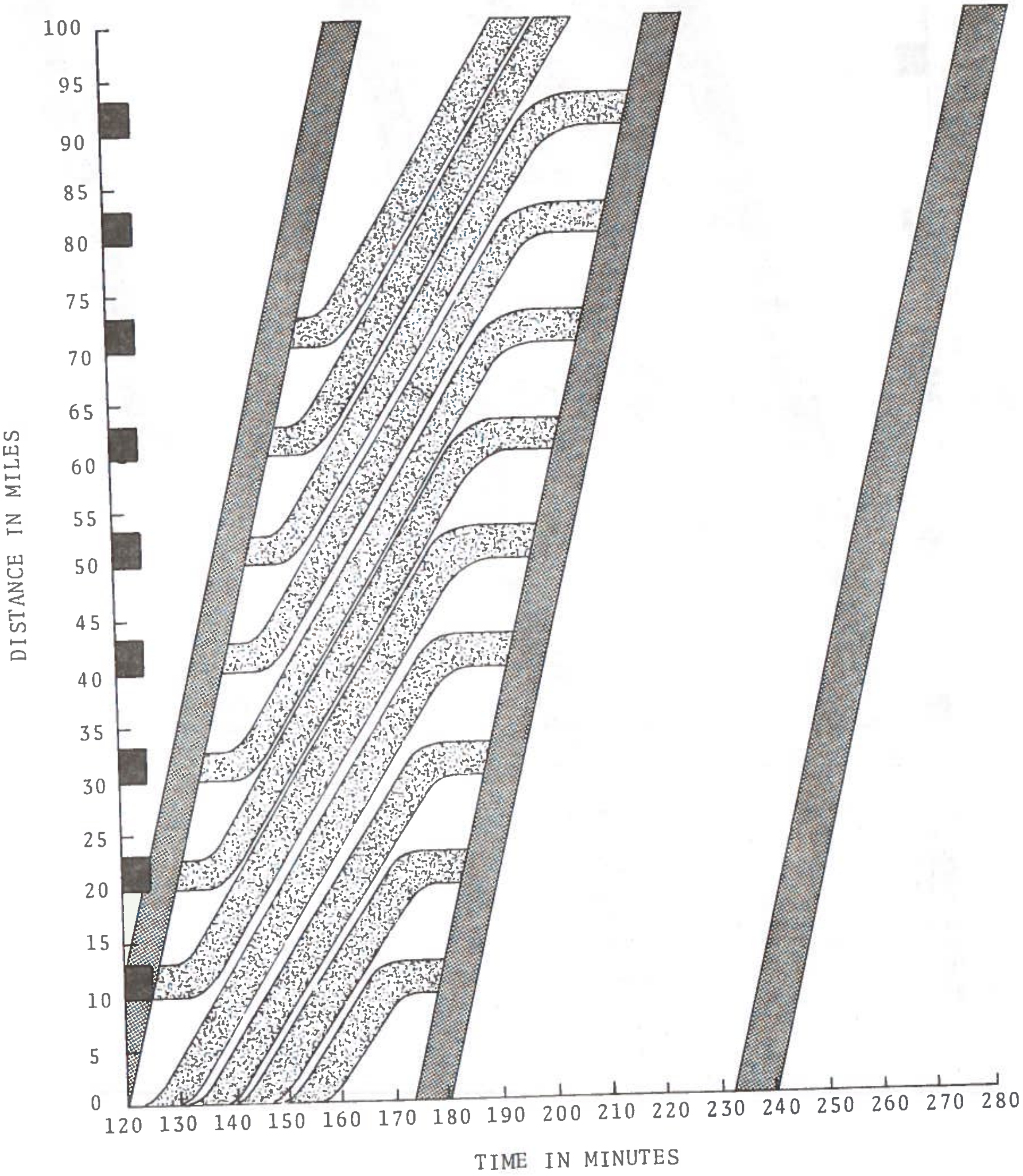

Figure 5-8. Train Graph V - Sidings Every 10 Miles HSPT at 125 MPH, Freight Train at 50 MPH

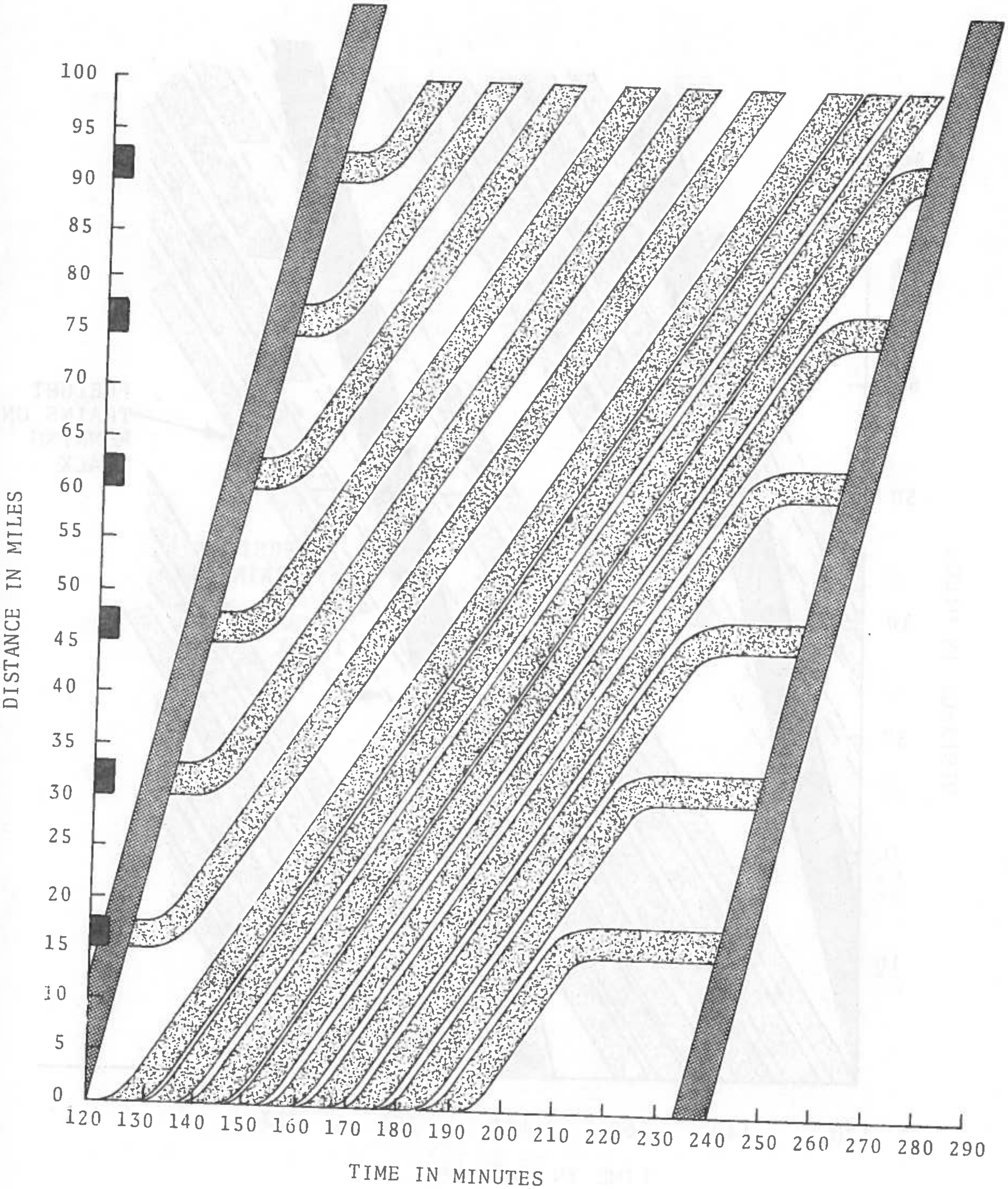

Figure 5-9. Train Graph VI - HSPT's Every 2 Hours at 125 MPH, Freight Trains at 50 MPH

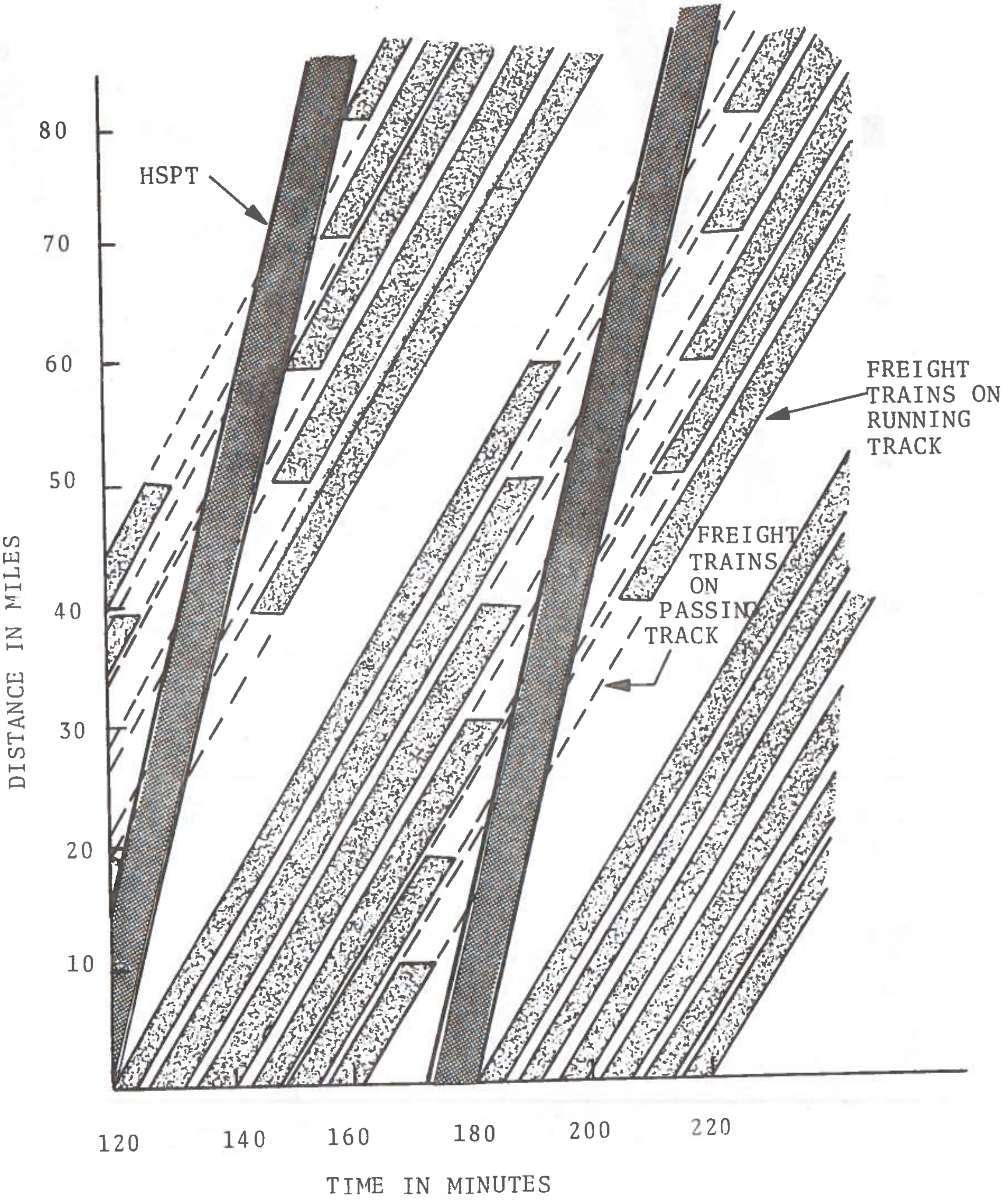

Figure 5-10. Case VIIa — Passing Tracks and Running Meets — Occupancy of the Running Track (Dashed Lines Indicate Freight Trains on Passing Track — Crossovers Located at 10-Mile Intervals)

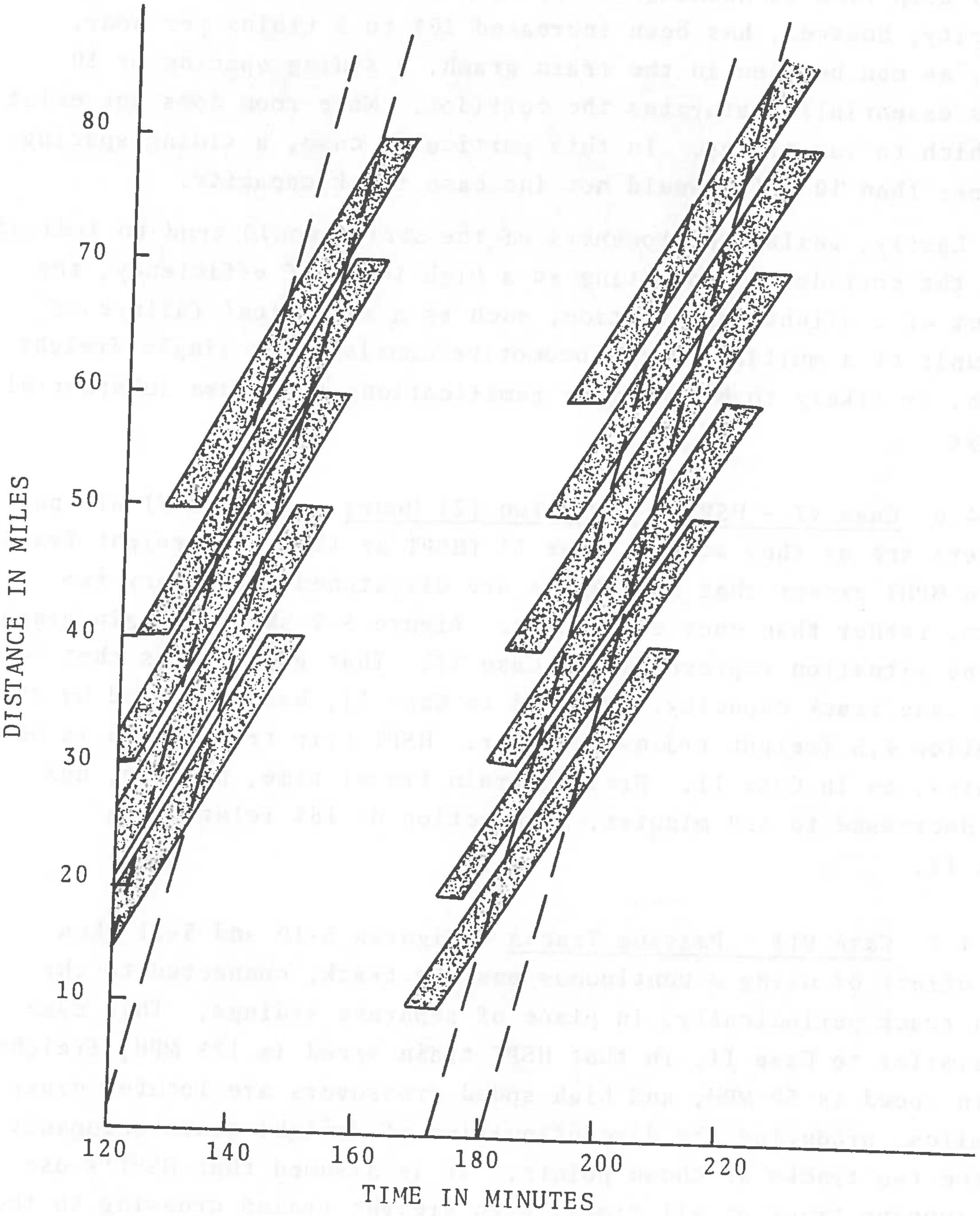

Figure 5-11. Case VIIb — Passing Tracks and Running Meets — Occupancy of the Passing Tracks (Dashed Lines Indicate HSPT's on Running Track — Crossovers Located at 10-Mile Intervals)

train trip time is unchanged from Case II at 380 minutes. Track capacity, however, has been increased 20% to 5 trains per hour. Also, as can be seen in the train graph, a siding spacing of 10 miles essentially saturates the corridor. More room does not exist in which to run trains. In this particular case, a siding spacing of less than 10 miles would not increase track capacity.

Lastly, while the closeness of the strips would tend to indicate that the corridor is operating at a high level of efficiency, the effect of a slight perturbation, such as a mechanical failure of one unit of a multiple-unit locomotive consist on a single freight train, is likely to have severe ramifications and cause substantial delays.

5.2.4.6 Case VI - HSPT's Every Two (2) Hours — In Case VI all parameters are as they were in Case II (HSPT at 125 MPH, Freight Train at 50 MPH) except that now HSPT's are dispatched once every two (2) hours, rather than once every hour. Figure 5-9 shows a train graph of the situation represented by Case VI. That graph shows that for this case track capacity, compared to Case II, has increased by 25% to allow 4.5 freight trains per hour. HSPT trip travel time is 96 minutes, as in Case II. Freight train travel time, however, has now decreased to 320 minutes, a reduction of 16% relative to Case II.

5.2.4.7 Case VII — Passing Tracks — Figures 5-10 and 5-11 show the effect of using a continuous passing track, connected to the main track periodically, in place of separate sidings. This case is similar to Case II, in that HSPT train speed is 125 MPH, freight train speed is 50 MPH, and high speed crossovers are located every 10 miles, producing the discontinuities of freight train occupancy of the two tracks at those points. It is assumed that HSPT's use the running track at all times, with freight trains crossing to the passing track as required. As can be seen in Figure 5-10, this approach would result in fairly high capacity for the running track (6 freight trains per hour), twice that of Case II, and a freight train travel time of 320 minutes, which is equal to that of Case II.

However, the passing track, as shown in Figure 5-11, is left virtually useless in terms of adding additional traffic, and certainly could not accommodate any reverse traffic.

The results of the train-graph analysis are summarized in Table 5-1, which shows operating characteristics for the various cases. Freight train travel time and track capacity are also compared to the freight-only situation. Cases III and IV, which involve the greatest disparity in speeds, accordingly create the most disruption. Case VI reveals that even relatively infrequent passenger service – every two hours – still has strong negative effects. (Examination of the graphs suggests the extreme impact that still-more-frequent passenger service would have.)

5.3 OPERATING EFFICIENCY

The negative effects on rail freight service when high speed passenger trains are introduced are substantial. It is important to keep in mind that increases in total freight train travel time, as well as decreases in line capacity, can have very severe ramifications. The costs of delaying a freight train are substantial. In order to increase the degree of schedule compliance, a detailed cost characterization should include the expenses associated with decreased freight car and locomotive utilization in addition to the costs of additional train crew hours, increased fuel costs, and the probable necessity of having to increase the power-to-weight ratios of the freight trains.

The characterization should also take into account the fact that detaining a train crew may involve more than just additional crew hours. Current ICC train crew regulations restrict to twelve (12) hours the amount of time that any crew can be on duty. Therefore, a delay may result in the necessity of using two train crews rather than one. Also, the true social effect of increases in total trip time may very well be more than the sum of the economic costs, if one considers recent experiences with both power and freight car shortages.

TABLE 5-1. SUMMARY OF TRAIN GRAPH ANALYSIS – CORRIDOR LENGTH 200 MILES. FREIGHT-ONLY CASE (AT 50 MPH) IMPLIES 240 MINUTES TRAVEL TIME, 7 TRAINS PER TRACK-HOUR

	Case						
Characteristic	I	II	III	IV	V	VI*	VII
Maximum Passenger Train Speed (MPH)	80	125	150	125	125	125	125
Maximum Freight Train Speed (MPH)	50	50	50	35	50	50	50
Siding or Crossover Spacing (miles)	15	15	15	15	10	15	10
Crossover Capability (yes or no)	no	no	no	no	no	no	yes
Passenger Train Trip Time (minutes)	150	96	80	96	96	96	96
Freight Train Travel Time (minutes)	320	380	450	525	380	320	320
% Change from Freight-Only Case	+33%	+58%	+88%	+118%	+58%	+33%	+33%
Track Capacity (Freight trains/Track-hour)	5	3	2	2	5	4.5	6.0
% Change from Freight-Only Case	-28%	-57%	-71%	-71%	-28%	-35%	-14%

*HSPT dispatched at two-hour intervals rather than one-hour.

In addition to increasing the cost of rail freight transportation, the introduction of high speed passenger trains may result in a decreased railroad share of intercity freight traffic. Lang, Reid, and others have found that a key factor in a shippers' modal choice is transit time reliability.[32] The addition of HSPT's into an existing rail freight corridor will quite likely decrease transit time reliability, and therefore may decrease the rail portion of intercity freight traffic.

Data gathered for the MIT reports mentioned above reveal that the likelihood of a mechanical failure resulting in a delay of an hour or more in this hypothetical corridor is approximately one such delay for every seven trains. While the likelihood of a mechanical failure is the same whether or not HSPT's are operating in a corridor, the congestion caused by the introduction of HSPT's would result in a greater number of trains being affected. A mechanical failure in one freight train, lasting one hour, could result in delays to as many as seven other trains if all trains were scheduled to operate under tight headways. Moreover, breakdowns or accidents could cause blockage of the corridor for days if extensive repair or cleanup is required. (It should be noted that such occurrences are by no means rare in conventional freight service.)

Finally, these calculations have been based on the assumption that very precise scheduling and speed control can be assured. In actual operations such accuracy might well be either impossible to achieve or unacceptably expensive, particularly when allowance is made for normal track maintenance, and equipment variations, weather, etc. Impact on operations could then be substantially greater than calculated.

5.4 SUMMARY

It has been shown that a substantial decrease in line capacity and increase in freight travel time is virtually certain to result

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[32] A. S. Lang and C. D. Mantland, "Reliability in Railroad Operations," Studies in Railroad Operations and Economics, Vol. 8, Report MIT R72-74, Massachusetts Institute of Technology, Cambridge, Mass., 1972.

for any case in which HSPT speed is markedly higher than freight train speed. A complete and detailed description of the particular corridor in question is necessary to assess the effect on track capacity travel time and operating efficiency of the introduction of high speed passenger service in any specific case. More generally, it is clear that as traffic densities and speeds increase, detrimental effects will increase for freight operations, and often for passenger service as well.

6. CONCLUSIONS

1. For passenger service at speeds of 100 to 125 MPH, the signal systems in existing freight-service corridors may generally be expected to permit safe operation with relatively little modification. This results from the markedly better braking performance possible for passenger trains.

2. For speeds in the 125-150 MPH range, it is likely that major signal system modification will be required in most corridors if safe operation is to be obtained within practical operating constraints.

3. A preliminary examination indicates the strong desirability of cab signal and automatic train stop equipment for high speed operation. However, a study far more detailed and comprehensive than was possible in this project will be required to establish well-founded signal and control system requirements for high-speed trains. Such an undertaking would necessarily encompass behavioral considerations, physical and technical capabilities and constraints, further analysis of accident statistics, and computer simulation. More generally, an effort of this nature could provide greater insight and more firmly-based regulations for lower speeds in both freight and passenger service. (Current Federal regulations allow passenger trains to operate at speeds up to 59 MPH in non-signaled territories, up to 79 MPH in areas equipped with an Automatic Block Signaling system alone, and up to 109 MPH in areas equipped with an intermittent Automatic Train Stop system. These regulations should be re-evaluated as signal and control systems are upgraded.

The publication of individual accident reports by FRA provides an excellent source of data for further studies in determining the causal factors in railroad accidents. This information can be used not only in regard to high speed passenger trains, but for freight and rail commuter operations as well. The efforts presented here should be considered only as the first step in a long and continuing analysis of train control requirements. It is highly desirable that this process continue.

4. Serious consideration should be given to research and development directed toward lower-cost signal and control equipment and systems.

The high cost of the equipment plus the poor financial health of the industry currently presents a major deterent to the installation of train control systems, in spite of the general view of the railroad signaling community that such devices do prevent accidents and save lives. The cost of upgrading an Automatic Block Signaling system to an Automatic Speed Control, continuous Automatic Train Stop,or a continuous Automatic Cab Signaling system is often approximately $30,000 per track-mile plus a substantial amount for each locomotive. Wayside railroad signaling equipment is almost universally built around relay logic. Often the cost of the relay hardware is approximately 50 percent of the total cost of the wayside equipment, installation labor making up the remainder of the cost. The major potential for improvement in this area appears to be via application of solid-state electronic technology, which has proven to be very effective in reducing the total system costs in other applications – process control, highway signaling, etc. However, the railroad environment is extremely difficult for solid-state equipment, and a thorough study will be required to determine both technical feasibility and economic benefits within the constraints of fail-safe operation and high reliability. This area is particularly relevant to HSPT operations, for which such systems are especially important.

5. Operation of a significant number of high speed passenger trains in a freight corridor will have a marked detrimental effect upon freight train capacity and speed, becoming more severe with increasing HSPT frequency and speed. Based upon these considerations alone, with no assessment of track structure aspects or safety, a strong case can be made for the use of dedicated (passenger-only and freight-only) tracks.

APPENDIX - STOPPING DISTANCE CALCULATIONS

A.1 BRAKING LIMITATIONS

The two classic limitations on freight train braking and stopping abilities have always been low adhesion and the very large ratio of the gross loaded weight to the light weight of freight cars. Conventional freight car brake rigging is designed to avoid wheel slide when the car is empty. This practice assumes an adhesion limit of about 9%, averaged from 0 to 80 MPH, and results in a deceleration rate of approximately 1.9 MPH/sec. for empty cars, assuming the reference level of a 20 psi brake pipe pressure reduction. The Association of American Railroads specifies 4.61 as the maximum ratio of gross loaded to gross empty weights for freight cars.[1] Since the rigging does not compensate for the extra weight, the same retarding or stopping force is applied to the loaded car as is applied to the empty car.[2] Thus, for the loaded car a reference level (20 psi) brake pipe pressure reduction results in a deceleration rate of about 0.4 MPH/sec. The curves shown in Figure A-1 indicate an average deceleration rate actually less than this due to the brake pipe pressure propagation time delay.

Conceivably, all new HSPT's could be equipped with an electro-pneumatic brake control system, so that the effect of pressure propagation time delays would be much less and become essentially insignificant. The ratio of gross loaded to light weight of a passenger train is on the order of 1.05 to 1.1, so that even in the event that each car is not equipped with load sensing devices, the rate of deceleration is essentially the same, empty or full. However, HSPT stopping distances are also limited by two factors: passenger comfort and wheel-to-rail adhesion. These are treated in the following sections.

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[1] G.M. Cabble, "A.A.R. Rules and the Cobra Brake Shoe," Railroad Friction Products Corp., Wilmerding PA 15148, April 1973.

[2] Recently devices have been introduced which do sense whether or not a freight car is empty or loaded, and adjust the braking force correspondingly. Cars so equipped, however, make up a small portion of the interchange fleet; no block signal system could have been or now could be designed assuming the existence of such devices.

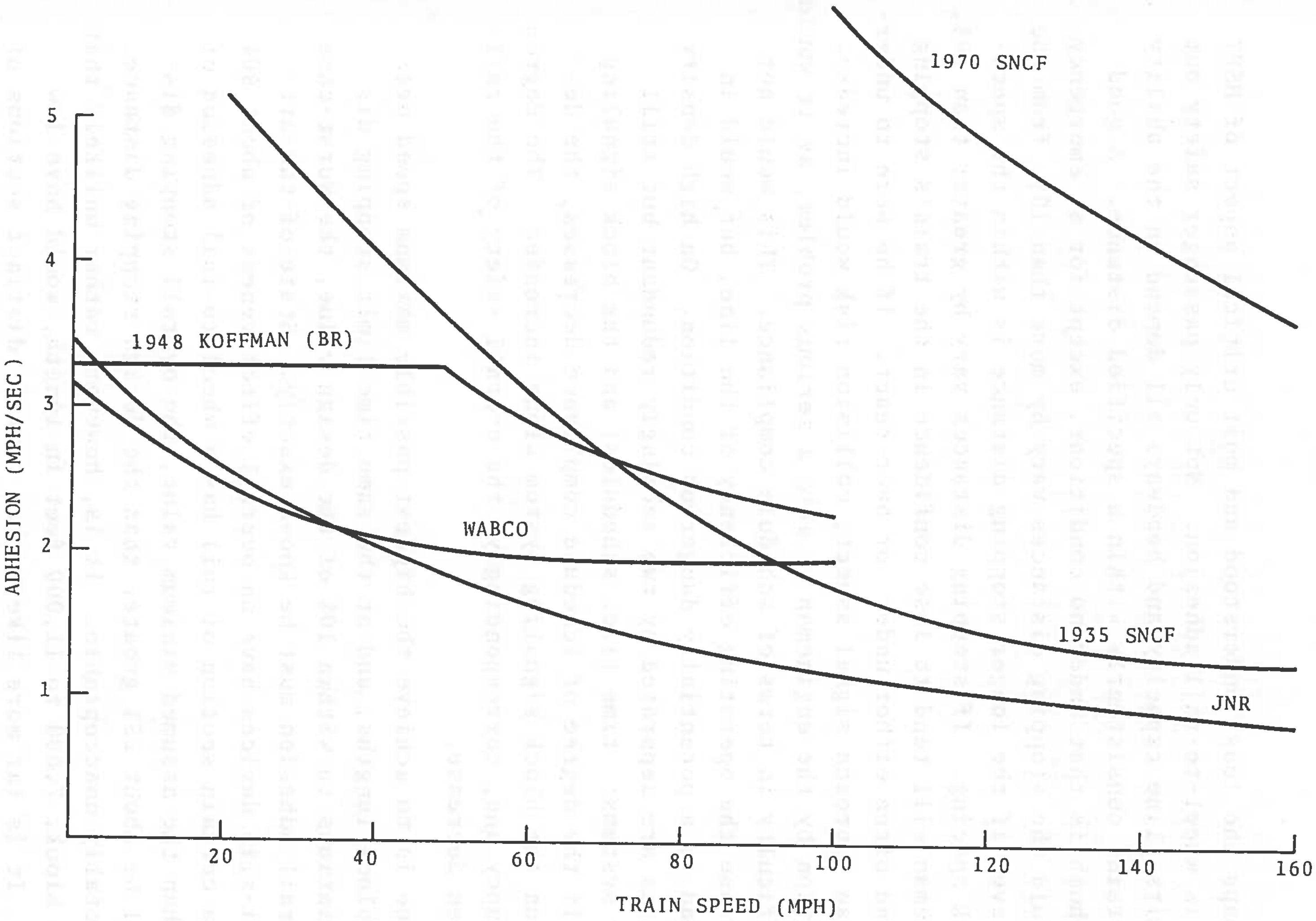

Figure A-1. Wheel-to-Rail Adhesion - Worst-Case Values

A.2 ADHESION

Perhaps the least understood and most critical aspect of HSPT planning is wheel-to-rail adhesion. Not only passenger safety but speed limits, line capacity and headways all depend on the ability to stop trains consistently within a specified distance. A good rule of thumb is that under no conditions, except for an emergency stop, should the stopping distances vary by more than 10% from the average, even if the longer stopping distance is within the specified block spacing. If stopping distances vary by greater than 10%, the engineman will tend to lose confidence in the train's stopping ability and often either under- or over-react. If he were to under-react on an approach signal aspect, collision risk would increase. Over-reaction by the engineman is also a serious problem, as it would cause difficulty in terms of schedule compliance. This would not only decrease the operating efficiency of the line, but would in itself lead to a potentially dangerous condition. On high density lines trains are separated by two seemingly redundant but still necessary systems: time (i.e. schedules) and the block signaling system. If the degree of schedule compliance decreases, the dependence on the block signaling system alone increases. The degree of redundancy and, correspondingly, the overall safety of the rail system then decrease.

If one is to achieve the highest possible maximum speed over existing block lengths, and at the same time limit stopping distance variations to within 10% of the design value, the worst-case wheel-to-rail adhesion must be known exactly. State-of-the-art wheel anti-slip devices have an overall effectiveness of about 80%. Thus, if a certain section of rail has a wheel-to-rail adhesion of 5% less than the assumed minimum value, the overall stopping distance will be about 25% greater than the design stopping distance. This is totally unacceptable. It is, however, rather unlikely that an entire block, 7,000 to 11,000 feet in length, would have low adhesion. It is far more likely that certain distinct sections of low adhesion would tend to cause momentary interactions of the anti-slip device. However, even in this case, the number of momentary anti-slip device reactions must be held to a minimum; again, the worst-case wheel-to-rail adhesion must be known exactly.

Figures A-1 and A-2 show plots, from different sources, of the assumed values for worst-case adhesion and the assumed values for typical adhesion on good rail. In terms of block spacings the curves of Figure A-1 are of principal interest, as the design parameter is the minimum adhesion. Figure A-2 is included primarily for comparison. As can be seen from the curves, there is considerable disagreement as to exactly how much adhesion actually exists. The 1970 SNCF curve shows a level of adhesion at 150 MPH 400% greater than the JNR curve at the same speed. The worst case according to SNCF, at 100 MPH, is about twice as high as JNR's value for good rail at 100 MPH. This disagreement has led to some confusion in the industry and may, in fact, lead to a potentially dangerous situation as well.

The JNR data, while probably accurate for their application, have limited usefulness for this study. The data were taken using JNR passenger cars on the Tokaido Line from 1961 through 1965.[3] The discrepancies appear to arise from the original JNR decision, taken at an early stage, to use a disk braking system without any form of wheel scrubbing apparatus.[4] Whenever comparison tests are done – there is apparent industry agreement on this – adhesion tests done with tread-braked vehicles always show higher adhesion values than do disk-braked vehicles.[5] While disk brakes do offer some clear advantages over tread brakes, the high tread temperatures of tread braked wheels (typically 300 to 500 degrees F) seem to be very effective in "burning off" moisture and oil films on poor or wet rails. Also, the dust particles generated during a tread brake application seem to improve adhesion in much the same way as does sand.

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[3] M. Fujii, "New Tokaido Line," Proceedings of the IEEE, Vol. 56, No. 4, April 1968.

[4] JNR did install wheel scrubbers, but only after the adhesion tests were completed.

[5] H.P. Roberts, "Improved Braking Raises BR's Inter-City Speeds," Railway Gazette International, February 1973.

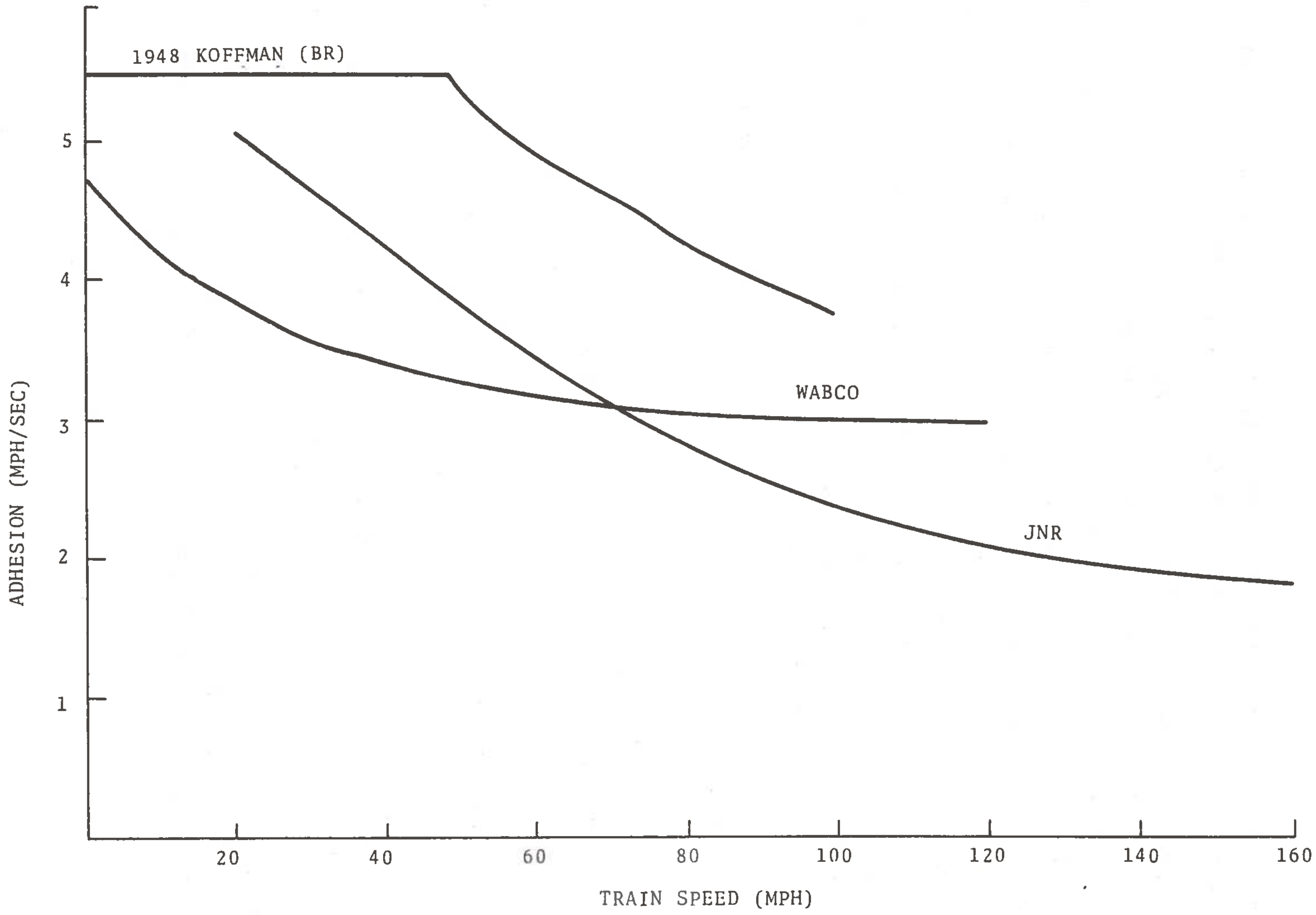

Figure A-2. Wheel-to-Rail Adhesion — Typical Good-Rail Values

The more recent SNCF data are interesting. For these tests, carried out in the spring of 1970, SNCF used a specially modified CC21000 locomotive with a 4,000 HP traction motor arranged to power only the front axle of the front truck. Water was sprayed directly in front of the front wheels. Using this arrangement, there was sufficient power to achieve slippage or to break traction, at speeds up to 200 MPH.[6] SNCF measured the locomotive's speed, electrical input power, and the traction motor operating efficiency, and was able to determine the maximum torque that could be applied without breaking traction as a function of speed. Knowing the torque, SNCF assumed that the weight on the front axle was equal to the locomotive weight divided by the number of axles. With the front axle load and the maximum torque known the worst case adhesion could be calculated and plotted. This approach may not be entirely accurate. First, the weight on the front axle of the front truck is not generally constant and is a function of truck design. The effect of a forward acceleration produced by front wheel drive exerts a moment about the front axle and places an extra force (weight) over the front wheels of the locomotive. This is analogous to what happens to a rear wheel drive automobile when, under heavy forward acceleration, the front end of the car rises and the rear end lowers due to the torques and the effect of the suspension.

The second concern with the SNCF test results is the effect of the unnatural and unrealistically large moment of inertia of the front axle. Current adhesion theory assumes zones of low adhesion, usually of limited length – over crossing frogs, switches, oil spills, etc. – and when one measures wheel-to-rail adhesion, these short sections should be measured exactly, since these short sections are what tend to cause wheel slip/slide. However, the large moment of inertia of the CC21000 locomotive's front axle tended to prevent any rapid increases in wheel speed, and thus during the SNCF

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[6] F.F. Nouvion, "SNCF Probes the 200 KM/H Speed Band," Railway Gazette International, August 21, 1970.

test wheel slip on short sections of low adhesion rail presumably did not have time to start.

The third problem with the SNCF tests is that good quality rail (even when wet, as was used for the SNCF test) is probably not a fair approximation of all possible rail under all possible conditions. Each of the above three factors would tend to cause inaccuracies in the data and would tend to yield higher values than is really the case. It is probably for those three reasons that no other adhesion test data have even approximated the 1970 SNCF data. It is unfortunate, but interesting to note, that shortly after SNCF's RTG trains – which assume adhesion values based on the 1970 SNCF data – arrived in the U.S. for Amtrak service, a brake application (in order to prevent a grade crossing collision) resulted in slid-flat-wheels, and the entire train had to be removed from service until the wheel grinding work was completed.[7]

The WABCO curve would seem to be an accurate estimate of the minimum wheel-to-rail adhesion likely to be found in the U.S. with tread-braked vehicles. The curve represents the adhesion assumed by the Air Brake Division of Westinghouse Air Brake Co. during the design of freight car brake rigging and brake shoes. A freight car equipped with WABCO brake rigging and brake shoes assumes a level of adhesion equal to the curve shown on Figure A-1.[8] For rail rapid transit systems with new welded rail, WABCO does assume an adhesion level considerable higher than the curve shown. The data upon which the curve is based were actually measured by WABCO over a long series of single-car stopping tests. Judging from the relatively infrequent nature of slid-flat freight car wheels caused by a non-emergency brake application, it would seem that the WABCO curve represents a safe estimate of the minimum level of adhesion likely to be found on mainline trackage. In fact, the curve may represent a slightly pesimistic estimate for the HSPT

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[7] Railway Age, November 12, 1973, p. 10.

[8] Air Brake Association Handbook, Management of Train Operation and Train Handling, Chicago, 1972 and Sales Literature, Westinghouse Air Brake Corp., Pittsburgh, Pa.

situation, which involves only mainline and not branch line trackage. All stopping distance calclations in this report are based upon the WABCO curve for speeds less than 100 MPH. The older 1935 SNCF adhesion curve is used for calculations above 100 MPH.

It is difficult to comment upon the 1948 Koffman data,[9] except to note that the British Railways, sponsors of the tests, have stopped using it, and are using the higher values of the new SNCF curve.[10] BR does, however, include a safety margin with the SNCF data.

Figures A-3 and A-4 show the worst-case adhesion limits of both the old (1935) SNCF curve and the WABCO curve, superimposed upon the adhesion demands assumed for non-emergency stopping for several HSPT's.

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[9] J. Koffman, "Adhesion and Friction in Rail Traction," Railway Gazette, 29 October 1948, p. 484.

[0] Roberts, op. cit.

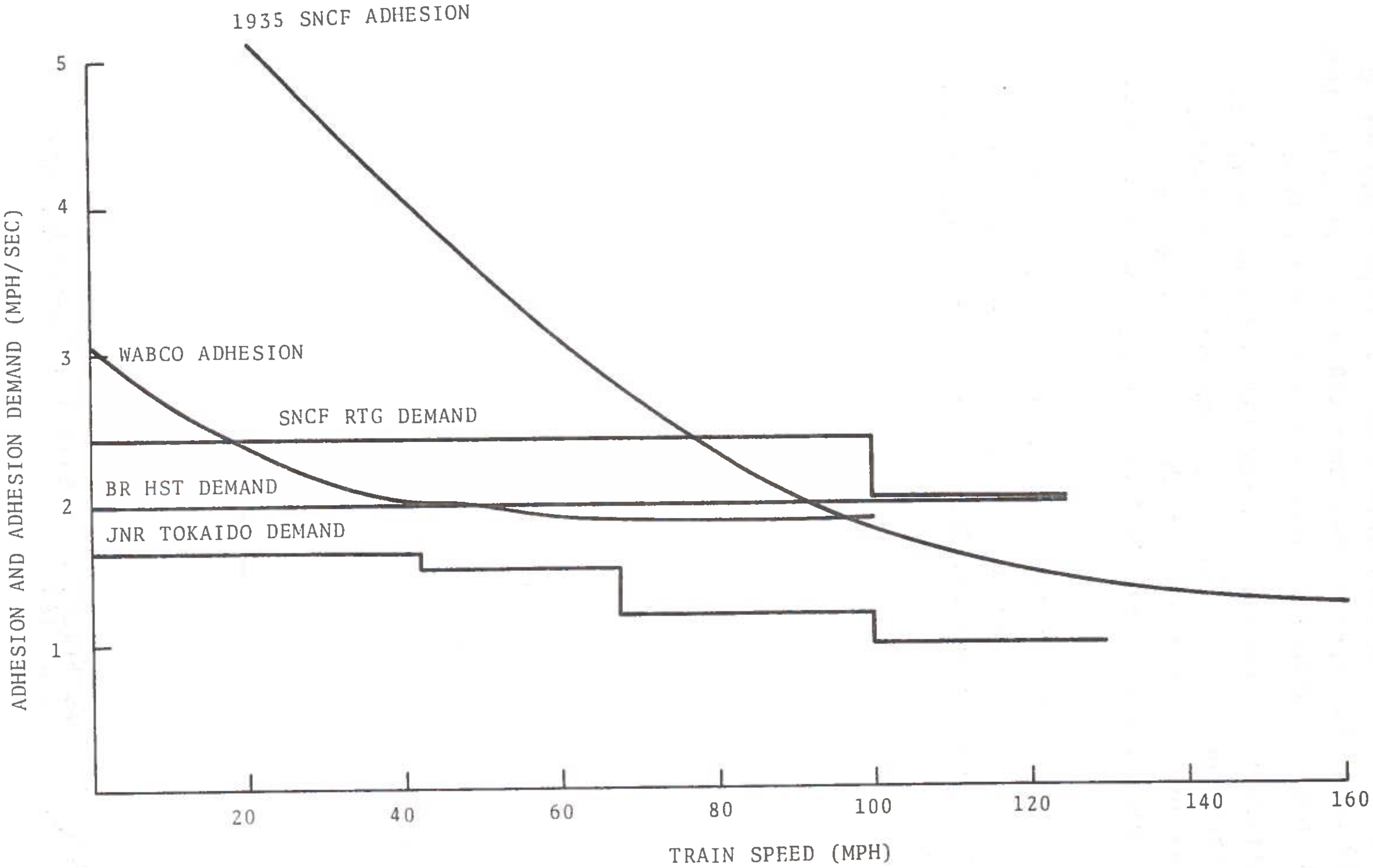

Figure A-3. Worst-Case Adhesion and Adhesion Demand Assumed for Three Foreign HSPT's

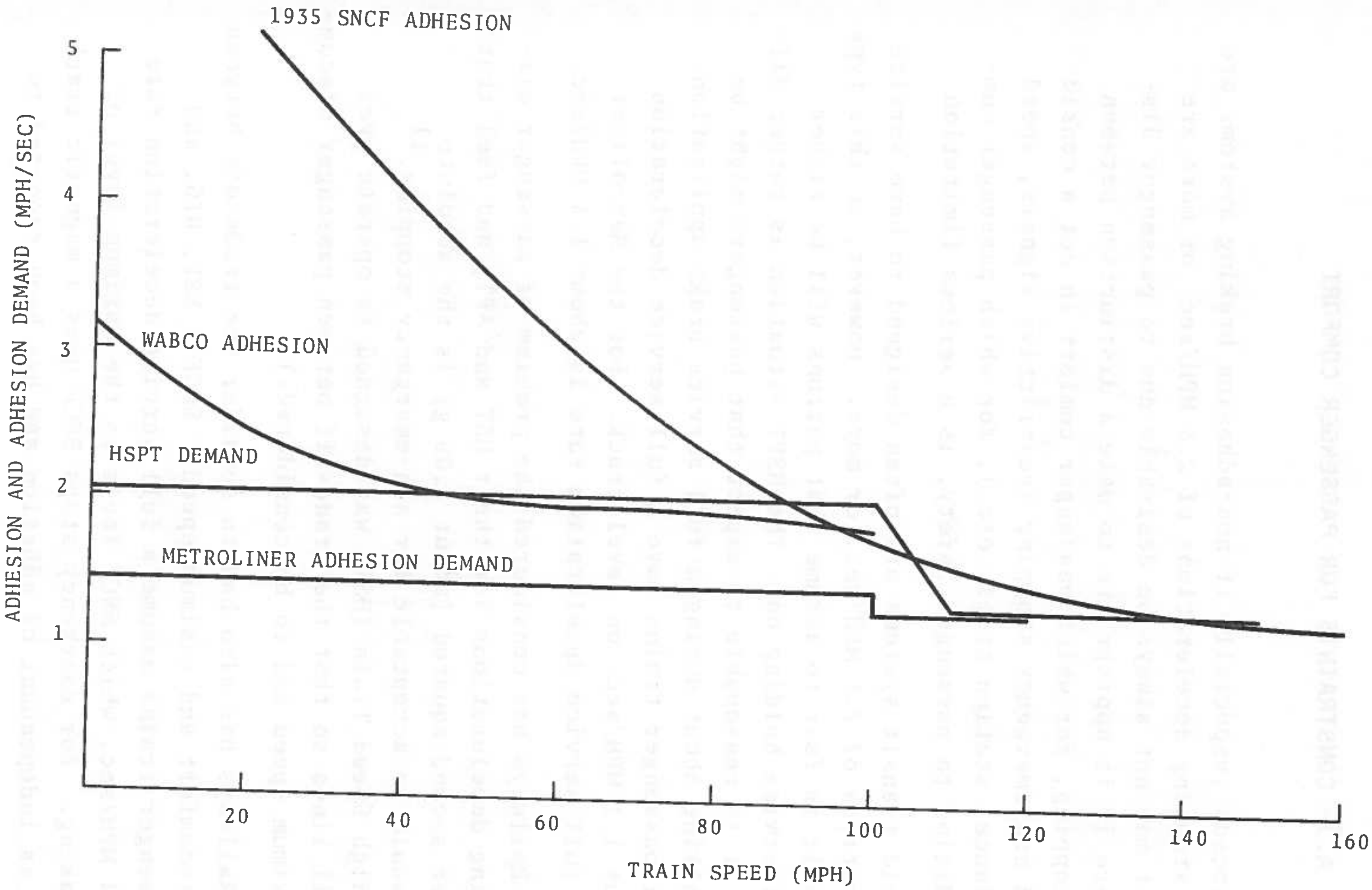

Figure A-4. Worst-Case Adhesion and Adhesion Demand Assumed for Metroliner and Hypothetical HSPT

A.3 CONSTRAINTS FOR PASSENGER COMFORT

At low speeds (especially if non-adhesion braking systems are considered) stopping decelerations of 2.5 MPH/sec. or more are possible but may not always be desirable due to passenger discomfort. Here it is appropriate to make a distinction between emergency stopping, for which passenger comfort in not a consideration, and non-emergency stopping (restrictive signals, speed limit compliance, station stops, etc.), for which passenger comfort, in addition to passenger safety, is a serious limitation.

Rail rapid transit systems are often designed to have service brake applications of 2.5 MPH/sec. or more. However, in this type of operation it is fair to assume that patrons will be either seated or otherwise holding on. The HSPT situation is rather different, and it is reasonable to expect that passengers might be eating or walking about during a full service brake application. Conventional passenger trains have a full service deceleration rate of about 1.1 MPH/sec. on level track. For the Metroliner the maximum full service deceleration rate is about 1.4 MPH/sec.

British Railways has considered the problem of passenger discomfort during decelerations for their HST and APT, and feel that 2.88 feet per second squared (about 0.09 g) is the absolute limit that would be acceptable for non-emergency stopping.[11] (Britain's High Speed Train (HST) was designed to operate over existing rail lines so that the trade-off between passenger discomfort and maximum speed had to be considered.)

French Railways has also had to consider the trade-off between passenger discomfort and maximum speed. SNCF's ERT, RTG, and TGV.001 passenger trains assume a full service deceleration rate of about 2.4 MPH/sec. which SNCF feels is the maximum level of adhesion braking. For emergency stops SNCF uses a magnetic track brake which is independant of adhesion and has been reported to

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[11] Ibid.

increase the deceleration rate by about 0.6 MPH/sec.[12]

The situation in Japan is considerably different than that in the United States. When the Tokaido Line was installed, JNR had the advantage of designing and constructing completely new (IPT-only) system so that high speed could be achieved without decelerations threatening to passenger comfort. The maximum full-service deceleration rate on the Tokaido Line is about 1.6 MPH.sec.[13]

JNR and United Aircraft have studied the responses of passengers subjected to varying levels of longitudinal accelerations and decelerations.[14] An examination of those data reveals that the point at which passenger comfort becomes a serious constraint appears to be between 2.2 MPH/sec. and 2.6 MPH/sec. The JNR data predict that 95% of the passengers subjected to a 2.2 MPH/sec.[15] deceleration would rate the experience as no more than "slightly uncomfortable." The corresponding figure for a 2.6 MPH/sec. deceleration is 90%. For comparison, an average takeoff or landing in a commercial aircraft subjects passengers to an acceleration or deceleration of about 11.0 MPH/sec.

The JNR data also indicate that the rate of change of deceleration, or jerk, is probably as important a constraint as is the value of deceleration itself. According to the JNR data, changes in the rate of deceleration on the order of 2.0 MPH/sec.^{2} are about the maximum design value that would be acceptable. At a jerk level of 2.0 MPH/sec.^{2}, JNR data predict that 95% of the passengers would

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[12] C. Dubois, "Braking the SNCF's Turbotrains," Railway Gazette International, February 1973.

[13] M. Fujii, "New Tokaido Line," Proceeding of the IEEE, Vol. 56, No. 4, April 1968.

[14] J. Carstens, Literature Survey of Passenger Comfort Limitations of High Speed Ground Transports, PB 168 171, July 1965; S. Urabai and Y. Nomura, "Evaluation of Train Riding Comfort Under Various Decelerations," Japanese National Railways, Vol. 5 No. 2, 1964.

[15] Data interpolation is required.

rate the loading at no more than "slightly uncomfortable." At a 4.0 MPH/sec.^{2} rate of change, 90% of the passengers would consider the loading no more than "slightly uncomfortable."

Thus the adhesion limits assumed for use in stopping distance calculations in the preceeding section appear to be within range of passenger comfort, as long as the brakes are applied gradually and not suddenly — a deployment time of 1.0 second would seem satisfactory. It does appear, however, that passenger discomfort, at present deceleration levels, is on the verge of becoming a serious constraint. Except for emergency stops, stopping distances are virtually as short as this limitation will permit.