Preview Information in Locomotive In-Cab Displays for High-Speed Trains

by
Jacob Einhorn

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ABSTRACT

Prior research has established the need for further aids for high-speed train control and the potential usefulness of preview information. The objective of this research was to examine the usefulness of preview information in the control of high-speed trains. Human-in-the-loop experiments were run on the MIT/Volpe National Transportation System Center high-speed train simulator. The primary goal was to examine whether the proposed information-aiding display improved safety and efficiency of train operation over an existing display, and, if so, how much of the provided preview information was useful. Secondary goals included comparing the data gathered from student subjects with that gathered from Amtrak engineers, as well as getting feedback from the Amtrak engineers on the realism of the simulation to be able to make recommendations for future simulator enhancements.

Engineer and non-engineer subjects performed similarly with respect to signal adherence and speed control. Preview information was found to be useful in both of these regards; the longer-preview and variable preview displays provided the best results. The preview displays were somewhat detrimental to accurate station-stopping, as subjects came to rely on the displays for help with stopping, though the displays did not provide high enough resolution to stop accurately. Future work with preview information should take into account the different resolution required at different speeds, as well as the rescaling the engineer is then required to do in his or her head. The engineers had better reaction times than the students when using the no-preview display, though the non-engineers performed better with the preview displays. Though the rail engineers generally reacted favorably to the preview displays, further work is needed to determine how the engineer allocates his or her attention between the displays and the out-the-window view, particularly in an environment in which they are more familiar with the physical characteristics of the train and track.

Thesis Supervisor: Dr. Thomas B. Sheridan
Professor of Engineering and Applied Psychology

Acknowledgments

This research is part of an ongoing project funded by the Federal Rail Administration (FRA) to examine various possible train control upgrades, particularly train automation and information aiding. This research was conducted at the Volpe National Transportation Systems Center near Kendall Square in Cambridge, MA, using an interactive train simulator developed jointly by the MIT Human-Machine Systems Lab and Volpe's Center for Human Factors Research in Transportation (see Chapter 2 for a further description of the simulator).

This paper is the fruit of many people's labor. I would like to thank Kari Kulaszewicz for her help and good nature; Steven Villareal for his help with the sound generation and the building of the locomotive cab; J.K. Pollard for his help with many different aspects of the simulation, from mechanical to electrical, hardware to software; Bob Dorer for his knowledge, time and effot; Ross Gill for his experience and good humor; Leslie Regan and Joan Gillis for their endless help, support and indulgence and Frank Sheelen for his technical expertise. Many people from the rail operators and locomotive manufacturers were helpful with their knowledge and frank opinions: Masahiko Horiuchi of JR East; Dick Bruss and Pat Kelley of Amtrak; Daniel Metaut and Phileppe Mingasson of GEC Alsthom; Bengt Lindwall of AdTranz; Howard Moody of the AAR; George Kuehn of IITRI; and Ron Berben of Amtrak. I would particularly like to acknowledge of Steven Jones and Joe Arcuri of Amtrak for their help in lining up subjects. The subjects themselves are owed a deep debt of gratitude for giving up their days off to help us with our work.

There were several people whose insight and effort were particularly helpful. Dr. Jordan Multer of the Volpe Center was a knowledgeable contact, an understanding supervisor, and a practical guiding hand. Dr. Thomas Sheridan was patient and thorough in overseeing the organization of the experiments; his knowledge and demeanor will stay with me for a long time. Dr. Ed Lanzilotta wrote much of the code that the MIT/Volpe train simulator is based on, and his guidance and effort (after he had already left MIT and the Volpe Center for "greener pastures") will serve as a reminder of how people of faith and wisdom should act. I thank my family and friends for their support and encouragement. And last, but by no means least, I thank my beautiful, intelligent, funny and caring wife, Shari Kleiner, without whom the success of this project would be neither as complete nor as enjoyable.

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Introduction: High-Speed Rail and Train Control

As trains travel faster and engineers are required to incorporate, analyze and act on more information in a shorter period of time, safety and efficiency may be at risk, as engineers may be unable to react properly to signal changes or other train control orders. This risk is compounded by the fact that high-speed passenger trains in the United States will share the track with slower-speed freight trains. In some other countries, such as France and Germany, managing train traffic with varying speeds has been dealt with, in part, by creating a separate high-speed train network—isolated not only from automotive trains and pedestrians, but from lower-speed trains as well. Separate guideways for high-speed passenger trains are not feasible in this country. There are simply too many miles of track to isolate them all in a manner that would be fiscally acceptable to the government, the private sector or the tax-paying public, due in no small part to the fact that passenger rail traffic in this country is not large enough to support such an investment. Track isolation is only one way to manage train traffic traveling at greatly varying speeds; other methods include automation ("control aids" such as cruise control, "control supervisors" such as automatic speed protection, or "control infrastructure" such as improved relays for track circuitry or switches) and decision aids (such as in-cab signals).

This research is part of a program funded by the Federal Rail Administration (FRA) to examine the effect of automation on operator performance and safety. Previous research performed at the MIT/Volpe simulator has focused on various types of decision aiding (Askey 1995). In particular, Askey found that higher levels of display aids that incorporated preview, predictive and advisory information resulted in safer and more efficient train operation, and were rated subjectively as imposing a lower overall workload than lower levels of aiding (see the end of this chapter for a further discussion of Askey's experiment). This research continues to examine preview information, and whether and how it helps engineers to make better decisions.

History of Train Control

Since the advent of the steam locomotive in the early 1800s and the opening of the first public train service in London in 1825, rail safety efforts have focused on effectively separating trains. In the earliest days of the steam engine in England, "the over-riding consideration was to get the locomotive to work...To make sure that no excessive speeds were run at the opening of the line the steam-hauled train was preceded by a man on horseback carrying a red flag. And that horse was not even trotting; it was walking!" (Nock 1987). Railway safety technology has come a long way since the days of horse-drawn signalmen, but not at the brisk pace one might expect. Initially, trains were separated by time intervals. In the "time-interval" or "open block" system, a second train was prohibited from passing a check-point until a prescribed time interval after the previous train had passed that point. The obvious problem with this system, which led to many accidents, is that once the initial train is out of sight of the check-point, it could be delayed for any one of a number of reasons—the second train would not know of the delay and, due to the large inertia of the train compared to the relative weakness of available braking systems, might not be able to stop in time once the engineer recognizes the need to brake.

The time-interval system, which was used long after telegraphic communication had been introduced, was replaced by the current "space-interval block" system, wherein a second train is not allowed to pass a certain point until the previous train has reached a fixed point ahead. The initial train's location is determined via human sight, mechanical tripping or electronic circuitry, and the resulting travel authorities for all trains are set (either manually or automatically) and relayed to all the intervening wayside signals. These signals serve to control the speed of all the trains in the system and can be set to any of a number of speed levels.[1] The adoption of the space-interval block system, along with the use of interlocking mechanisms (which protect areas around switches and crossovers by mechanically linking the signal aspect with the switch state and preventing occupied switches from being thrown) and automatic continuous braking systems (which provide full-service braking power to each car in the event of a loss of power or a break-in-two), constitute the three most important safety advances in train control of the 19th century (Mashour 1974). Important safety advances in this century include automatic signaling, in-cab signaling (replicas of the wayside signals for the current block, and automatic train protection (ATP—which protects the train from overspeed violations by automatically applying the brakes when the speed limit is surpassed by a specified amount for a specified period of time).

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[1] The number of speed levels and the appearance, or "aspect," of each signal level is determined by the company that owns the track. These aspects are quite varied throughout the country.

Today the signaling system in a space-interval block system is designed using "fail-safe" principles, as is the train's braking system. That is, these systems are designed in such a way so that a failure of the system will result in a "safe" situation—in the case of a signal circuitry failure, the signal is set to "stop" (red) by a pendulum that is released as a result of a loss of electricity; a loss of brake pressure causes the brake shoes to be applied (i.e., it is the normal pressure in the brake pipe that restricts the brake shoes from being applied). As a result, many of the railway accidents that occur have been associated with humans either missing or misreading signals.[2] The weak link in the signal-control loop (see Figure 1.1) is the train engineer's detection of, and response to, periodic visual signals, which is currently the focus of many train

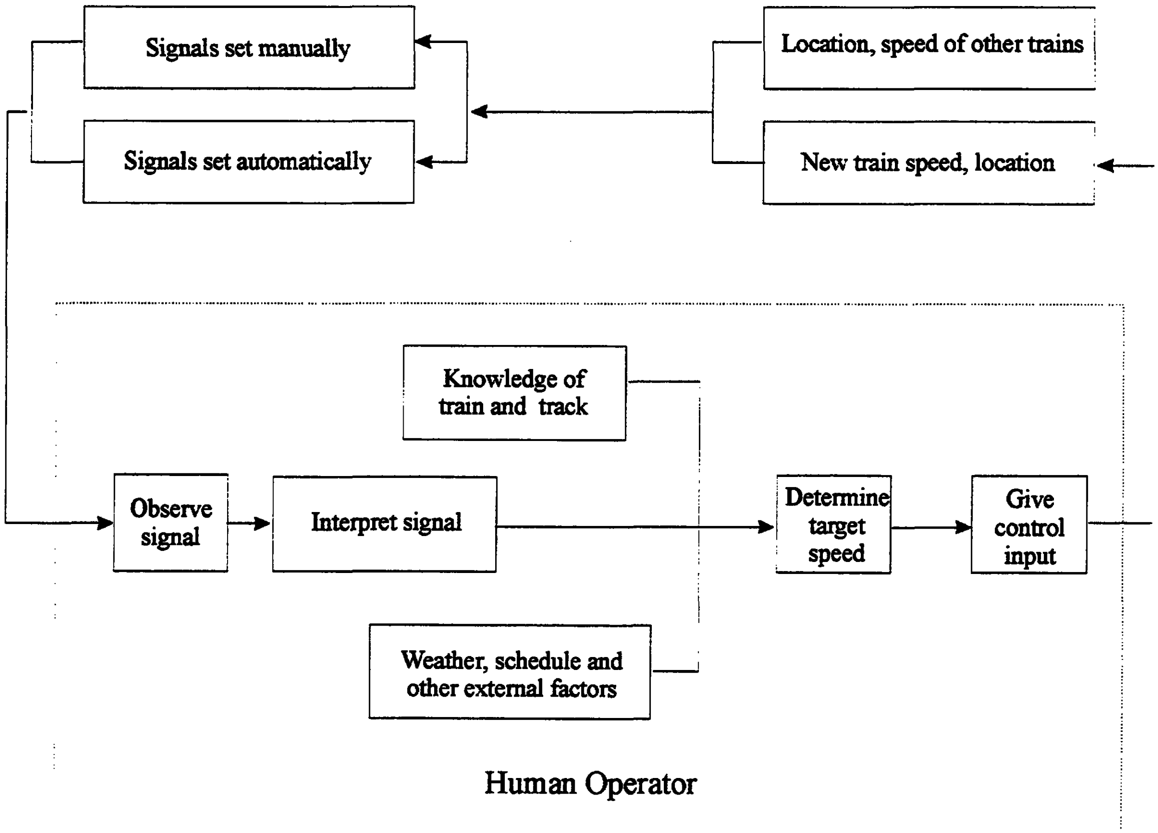

Figure 1.1: Train Control Information Loop

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[2] The number of train accidents has been relatively constant over the last ten years (between 2,500 and 3,000 per year). "Human factors" and "signal and track defects" are consistently the two leading causes of these accidents, each accounting for between 31% and 37% of all accidents each year (FRA 1996).

control safety enhancement efforts. It is not surprising that human engineers occasionally make mistakes—they not only have to remember the previous signal, but also have to constantly be aware of the gradients, curves and permanent and temporary speed restrictions of the road ahead, in addition to the current schedule and the acceleration and braking characteristics of the "consist" (or the combination of cars that make up the train) in all types of weather conditions. Furthermore, they have to make quick and accurate mental calculations based on all of this information in order to control the train properly.

Automation

Some of the most visible train control safety advances of this century have focused on aiding the accuracy of humans' observation of, interpretation of, and reaction to authority signals. These advances include increases in the visibility range of wayside signals, automatic signaling, in-cab signaling, and various forms of automatic train control (ATC) which may apply the brakes to some degree if the train exceeds the signal at a given point. For example, for a train to receive a waiver to exceed the national 79 mph speed limit, the train must be equipped with in-cab signaling and ATP. Both of these requirements are of the train control infrastructure. However, we must draw a distinction between *direct train control* and *decision aids*. ATP is train control in the literal sense, in that it is a tool by which the train is directly controlled (in this case automatically by the logic built into the cab); the in-cab signal, on the other hand, is a piece of information that the engineer uses, along with much other data, to decide how to control the train. Efforts to improve train control have focused both on direct train control tools (such as centrally-controlled switches), as well as on decision aids (such as in-cab signals, fail-safe gravity relays for roadside signals, etc.). Unfortunately, however, most of the track in this country still does not have the track circuitry to support in-cab signals, and some portions of the network still rely on voice communications to transmit authority notices.

Rail traffic, both passenger and freight, has not enjoyed the popularity in the United States that it has in other areas of the world such as Europe and Japan, though this was not always the case. As recently as 1955, rail transportation accounted for almost 40% of all commercial passenger traffic, with bus and air travel each accounting for about 30%. By 1990, air travel had captured 90% of such traffic, with rail at just 3% (Wilner 1994). Two main factors in this drop in ridership are cost and speed of travel. In order to increase safety and efficiency, improved train control and decision aiding must be implemented concurrently with upgrades to the track and other rail infrastructure.

As the German Inter-City Express (ICE) high-speed passenger trains and the Washington, DC Metro subway trains have shown, technology that allows completely automated train travel exists (even though a human operator is inevitably present, in at least a supervisory role). The research community as well as the general public have paid increasing attention to automation of rail operations in the United States over the past decade, as ATCS (Advanced Train Control System) and other train control systems have gained notoriety. The ATCS guidelines, proposed jointly by the Association of American Railroads (AAR) and the Railway Association of Canada (RAC), have acted as a set of suggestions around which many alternative systems have been developed (Judge 1995; Progressive Railroading 1987; Progressive Railroading 1991; Haakinson et al. 1994), though no system has become fully operational in revenue service. (See the chapter titled, "State of the Industry With Respect to In-Cab Displays" for further descriptions of such systems.)

Automation of rail travel has several benefits, particularly with regard to the vigilance decrement that humans experience over a prolonged period of time. For instance, studies have shown that

> ...it is impossible for even a highly motivated human being to maintain effective visual attention towards a source of information on which very little happens, for more than about half an hour. This means that it is humanly impossible to carry out the basic function of monitoring for unlikely abnormalities, which therefore has to be done by an automatic alarm system connected to sound signals (Bainbridge 1987).

Furthermore, humans can not process data as quickly or as consistently as machines can. With the long periods of monitoring, the larger of amount of information to be processed, and the relative dearth of abnormal control inputs or critical scenarios, rail travel seems to be an area to which automation is particularly well-suited.

There are, however, some potential problems with automation of train operation that require examination—particularly that operators who are not in on-line control of a system, and don't have much experience handling particular critical scenarios, may not be able to react properly when that scenario occurs, due to complacency or lack of training (Bainbridge 1987). Other problems with full train automation include the possibility of improper baseline information being entered by the engineer and track obstacles (or other abnormal circumstance) not being detected by the automation (FRA 1994). One of the first studies done using the train simulator at the Volpe National Transportation Systems Center to evaluate automation in high-speed train operation concluded that if the train is fully automated, the operator's workload is too low to keep him/her aware enough of the surroundings to react to failure scenarios as safely and efficiently as in a less automated mode, but that automation level has little effect on detection of failure modes external to the cab (Lanzilotta 1996).

In this project, we assume that direct train control and train automation can only partially solve the problems inherent to high-speed rail in this country. If we begin with the premise that there is a human operator in the cab and that he or she has at least partial control of the train at all times, we must focus on providing the necessary information so that the operator can make the safest and most efficient decisions possible under any circumstances. Not only does the engineer need to be well-informed (i.e., be a part of the information loop—see Figure 1.1) during manual train control, but it is critical that the engineer be able to react equally well both when train automation fails and when a scenario would warrant that the engineer take control of the train from the automation. Thus, the operator must be aware of the operative level of automation at all times and be in a position to make control decisions if need be, highlighting "the irony that the more advanced a control system is, so the more crucial may be the contribution of the human operator (Bainbridge 1987)."

Decision Aids

Another study (Askey 1995) that was run concurrently with the one mentioned above examined the effects on operator awareness, safety and efficiency of varying levels of information provided to the train operator. Particularly, this study examined whether extra information overloads the operator to the point where the operator can not react to an unexpected scenario or perform a secondary task in an acceptable manner. In that study, Askey investigated several levels of decision aiding, each of which incorporated all the information included in the next lower level (see Table 1.1). Askey found that efficiency[3], station-stopping accuracy, schedule adherence, and reaction time to unexpected signal changes improved with increasing levels of display aiding, and were best with the highest level of aiding and the most information (advisor display, which incorporated the information from all of the lower-level aids as well). Moreover, though the more complex aiding increased operators' "head-down" time (i.e., the time they focus on their dashboard, and not out the window), the experimental subjects rated the most complex display as imposing the lowest overall workload and preferred it over any of the lower-level aiding displays.

Basic	Preview	Predictor	Advisor
current- and next-block signals	effective speed limit information for a certain, multi-block preview distance	maximum service and emergency braking curves, along with a future location prediction	advises on the optimal speed trajectory to satisfy all speed and schedule constraints with the minimum expenditure of fuel

Table 1.1: Askey's Display Aiding Levels

In a very simplistic way, Figure 1.2 indicates the dilemma posed by the fact that increasing train speeds are not compensated for by a corresponding increase in a human operator's rate of information processing. In other words, while the time-rate of information presentation can theoretically increase without bound, the operator's perception and control (or action) rates are bounded at some maximum level. Therefore, there is a point at which the operator is being fed information faster than he/she can process and/or act on that information. Furthermore, the time the engineer has to act on that input—if action is required by a certain location, as in the case of a signal change—is reduced by higher speeds. One obvious solution to this dilemma is to reduce the inputs per unit distance (e.g., spread out the signals by increasing the block lengths). However, the operator will still be limited by the maximum reaction time available, which is governed by speed and visibility. Thus, in aiding the operator to observe, interpret and act on impending signals, we should focus our efforts on increasing visibility, or preview distance.

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[3] Measured by a weighted sum of energy consumption and schedule deviance.

Askey's proposed decision aids were motivated by a desire to compensate for such human limitations in signal detection and information processing that are made more significant by high-speed locomotion. A separate study run at the IIT Research Institute (IITRI) examined the efficacy of the proposed ATCS displays with respect to safety and efficiency of operation in light of these same deficiencies (Kuehn 1992). That study concluded that the ATCS Level 30 display, which incorporates a gradient, authority and speed restriction preview for five miles ahead of the train, resulted in increased safety (as measured by the number of speed violations and red signal overruns) as well as having the "concomitant result...that the ATCS group produced significant reduction in fuel consumption over the conventional paper warrant group." These initial results, which highlight the importance of continued research in the area of decision aids for locomotive engineers, beg the question of how such information should be presented to the engineer. In particular, the engineer must be able to integrate the information into his/her view of the engineer's job in a meaningful way, rather than simply learning a Pavlovian response to some stimulus, which would not aid decision-making in critical scenarios. As one of the Amtrak engineers who participated in this research put it, the engineer does not want to "just nurse a machine" with a control system that "takes away the engineer's creativity."

System

$$\underset{\textit{information distance-rate}}{\left(\frac{\text{inputs}}{\text{distance}}\right)} * \underset{\textit{speed}}{\left(\frac{\text{distance}}{\text{time}}\right)} = \underset{\textit{information time-rate}}{\left(\frac{\text{inputs}}{\text{time}}\right)}$$

Human

$$\underset{\textit{maximum reaction rate}}{\left(\frac{\text{reactions}}{\text{time}}\right)_{\text{max}}} \longrightarrow \underset{\textit{maximum control rate}}{\left(\frac{\text{actions}}{\text{time}}\right)_{\text{max}}}$$

$$\text{average reaction time available} = \left(\frac{\text{inputs}}{\text{time}}\right)^{-1}$$

$$\text{maximum reaction time available} = \left(\frac{\text{visibility}}{\text{speed}}\right)$$

Figure 1.2: Processing Rates

Goals of This Research

1. This research examines the concept of preview information—information about the status of

the track some distance ahead of the train—which is expected to aid operators by partially compensating for the decreased signal processing time imposed by higher train speeds. Such preview information may include the signal speed, the civil speed, the effective speed or the track occupancy—data the engineer uses to make decisions regarding control input. The hypothesis is that providing the engineer with this information farther in advance will allow the engineer to make better (i.e., safer and more efficient) decisions in the time available. Is preview information useful, and if so, how much preview information is good? We have sought to answer these questions by running human-in-the-loop experiments with two groups of subjects—one consisting of rail engineers, the other consisting of MIT students—at the MIT/Volpe high-speed train simulator.

2. This research represents the first time rail engineers have been used as subjects at the MIT/Volpe simulator (previous experiments were run with MIT students as subjects); as such, a secondary goal of the research was to examine how the data received from rail engineers correlates with that received from student subjects.
3. A third goal of the research was to get rail engineers' feedback on the realism of the simulation—we have made extensive upgrades to the simulation (including adding a cabin environment; track, engine and alarm sounds; and more realistic control inputs) since the last set of experiments was run towards the end of 1995, and we are interested in anecdotal feedback on the efficacy of those upgrades and areas for future improvement.

To determine the course of high-speed rail in this country, we must understand the technology being applied by those countries who have already implemented rail operations at higher speeds. As such, the state of development with respect to in-cab locomotive displays in the various countries operating rail networks at high speeds was examined. Based on this information, along with interviews with train engineers, locomotive manufacturers, and train line operators, an in-cab decision aid was proposed and tested on the MIT/Volpe simulator. This thesis concludes with specific recommendations regarding preview information and other aspects of in-cab displays.

II: State of the Industry With Respect to In-Cab Displays

There are several organizations or entities that directly influence the state of the rail industry around the world. In this country, the American Association of Railroads (AAR), the trade group comprised of the largest freight rail companies along with Amtrak, develops specifications and guidelines that its members are encouraged to follow. Over the past decade, the specifications that the AAR has developed in conjunction with Railway Association of Canada (RAC—AAR's Canadian counterpart) to govern rail system automation have had a prominent effect on research and development efforts in that area. The rail operators themselves, both passenger and freight, develop their own requirements, driven by industry agreement or internal research, that they pass along to the manufacturers to fulfill. These rail operators include Amtrak in the United States, *Swedish Rail* in Sweden, the Japan Rail (JR) companies in Japan, Societe Nationale des Chemins de Fer Francais (SNCF—the French National Railways) in France, and Deutsche Bundesbahn (DB—German National Railway) in Germany. And finally the manufacturers, who are most directly involved in the development of the technology, may make recommendations to the operating companies, based on their technical knowledge and experience. These manufacturers include General Electric (GE) in Harris, PA; Asea Brown Boveri (ABB), which merged with Daimler-Benz in 1996 to form Adtranz; France-based Bombardier; and General Motors (GM). What follows is a brief overview of the current state of development of some of these entities with respect to in-cab displays and train control in general.

Sweden

ABB manufactures Sweden's high-speed trains, the X2000, the first of which was put into operation in 1990. Though Sweden's 19th-century rail network has been upgraded over the years, the network is characterized by its numerous curves, hampering plans to increase operating speeds due to the tremendous lateral forces on the passenger that would result. Furthermore, because of Sweden's rather sparse population[4], it was not considered economical to construct dedicated high-speed guideways. Consequently, Statens Jarnvagar (SJ, or Swedish State Railways) put its effort into redesigning the running characteristics of the cars to increase

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[4] Sweden is approximately the same size as California, but with a population of only about nine million.

speeds by up to 35% in curves (to 125 mph) and over 50% on straight track with no decrement in ride quality. The X2000 achieves these goals with two improvements over traditional rail cars: A mechanism that tilts the cars inwards in curves (thereby decreasing centrifugal forces on passengers in the cars) and the improved running characteristics of the "soft" bogies (which allow the front and rear wheels of each bogie to rotate independently, thereby decreasing rolling resistance around curves. The resulting smooth rides has received good reviews from wide quarters, particularly during its tour of the United States in 1994 (Wilner 1994).

SJ has a sophisticated automatic train control (ATC) system in operation over its entire rail network that is not specific to high-speed trains. Under this system, the current- and next-block signals are displayed in the cab (see Figure 2.1). If the train's speed exceeds 10 km/hr (about 6 mph) above the permitted speed, the computer will stop the train. The computer will also stop the train if the operator does not reset the alerter at least once each minute, if the gates at a grade crossing are not lowered in time, or if the automated induction loop system detects a train stuck in a grade crossing (FRA 1991a). As all trains operated in Sweden are required to be compatible with SJ's ATC system, the X2000 is differentiated from other trainsets with respect to in-cab displays only by its fault indication panel, which is intended to aid the engineer in understanding errors and possibly avoiding unnecessary stops for minor faults.

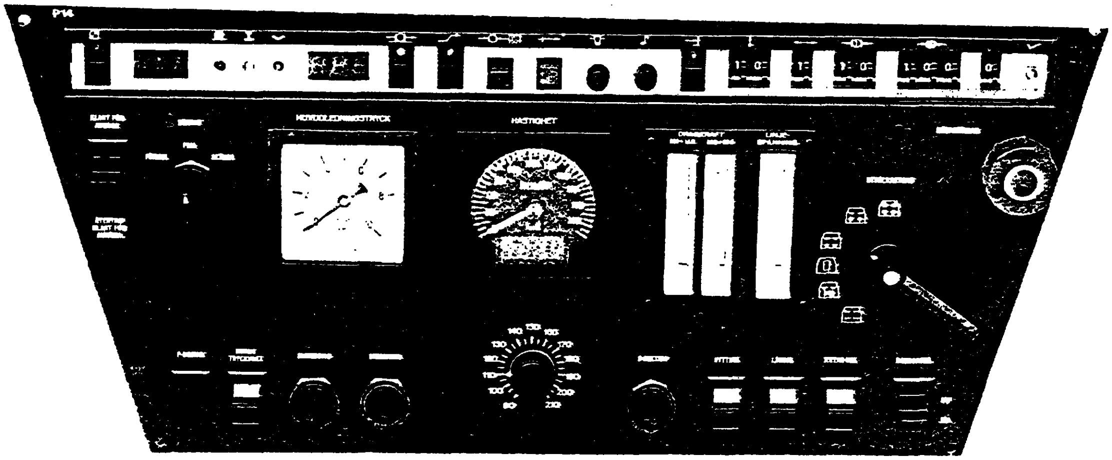

Figure 2.1: X2000 Instrument Panel (courtesy of Adtranz)

The X2000 in-cab displays used for train control and fault indication present a combination of digital/analog and electrical/mechanical items. The brake pressure and current speed (the two largest displays on the instrument panel) are displayed on circular analog dials. The tractive effort and line voltage, displayed to the right of the speedometer and brake pressure gauge, are displayed on vertical linear gauges. To allow the ATC system to make its calculations properly, the operator must enter the train's length, maximum speed, braking capacity and brake delay via the thumbwheels situated above and to the right of the line voltage gauge. The system indication panel to the left of the train control panel (see Figure 2.2) consists of twenty back-lit, color-coded lamps, some of which must be interpreted in combination with information given in the fault indication panel above the windscreen. The combination of display paradigms evident in the X2000 gives the impression of a system pieced together over time, and indeed recent photographs of the X2000 cab look much like SJ cabs from the early 1980s.

Figure 2.2: X2000 Fault Indication Panel (courtesy of Adtranz)

The display item that stands out in comparison to other countries is the digital display of both the current- and next-block signal, in the upper left-hand portion of the display panel. Providing the next block's signal allows the engineer more time to react to an upcoming signal change, though the operator is still required to know the distance and time to the beginning of the upcoming block. The ATC system itself is sophisticated and seemingly quite robust, yet it relies on engineer input of train characteristics, like the German system (described below).

Japan

The high-speed trains operated in Japan, the Shinkansen, are operated throughout the country on dedicated rights of way. There are five different types of Shinkansen power cars in use: 200 (put into production in 1981), 400 (1990), E1 (1993), E2 (1994) and E3 (1994). These five different power cars use three different types of in-cab displays: MON1 (200), MON4 (400 and E1) and MON10 (E2 and E3). The MON4 and MON10 displays are software-generated displays that give information regarding train location and speed, as well as a graphical representation of consist and brake status (see Figures 2.3 and 2.4). The current block speed limit is indicated by a lighted dot at the perimeter of the speedometer[5]. Currently, the operator is not given any information regarding braking distance, distance to the next block, grade information or other trains' locations.

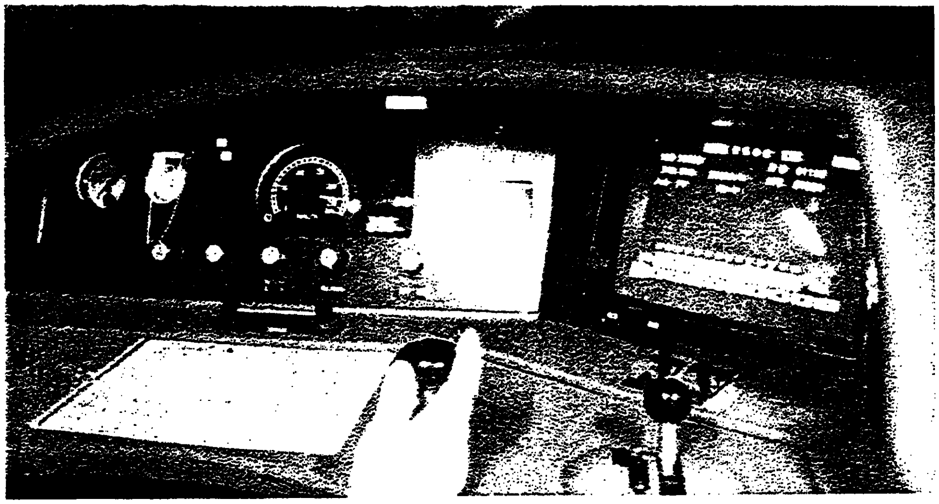

Figure 2.3: Shinkansen MON4 Display (courtesy of JREast)

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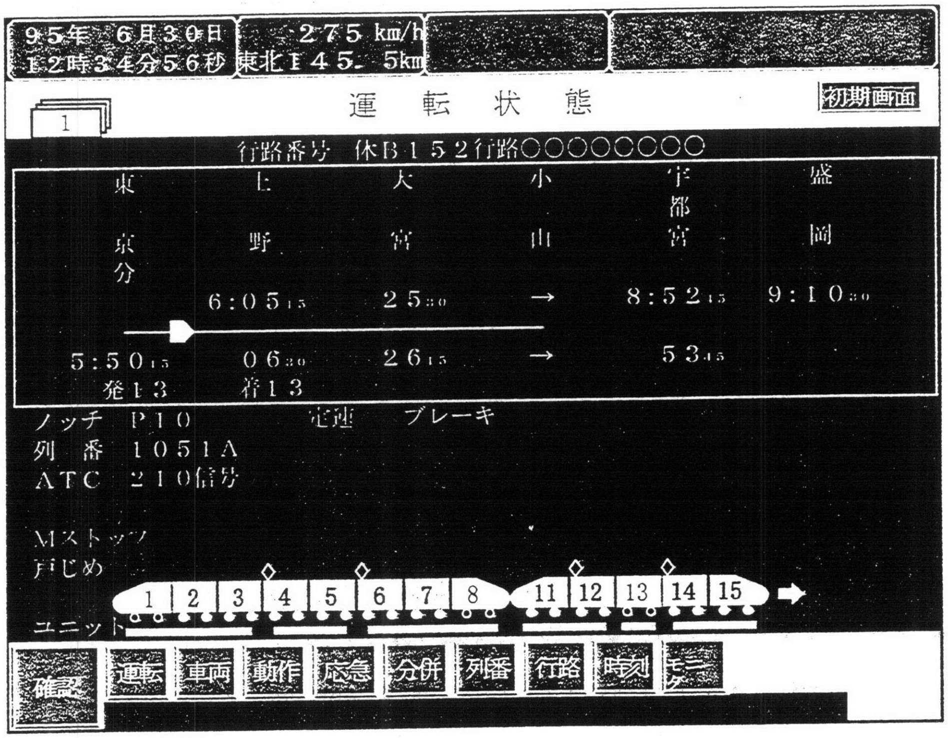
[5] It is interesting to note that the earlier displays (series 200) used a linear speedometer. At the engineers' request, the next generation of displays (the MON4 in the series 400 and E1) contained circular speedometers. When the most recent displays were developed (the MON10 in the series E2 and E3), the engineers requested that the displays revert to using linear speedometers. This is opposite to Amtrak's recent experiences in this country: The Genesis locomotive built by GE, which contained the first software-generated display used in passenger trains in this country, contained a linear speedometer. When the latest round of cabs was purchased from GE, for operation beginning Fall 1996, one of the few requests from the engineers was to return to circular speedometers like the hard-



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ノッチ P10　定速　ブレーキ

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ATC 210信号

Mストップ

戸じめ

Figure 2.4: Shinkansen MON10 Display (courtesy of JREast)

In addition to these Shinkansen displays, there are various other displays in use on Japan's conventional trains. There has recently been a strong push for standardization of in-cab displays to improve general design and reduce operator confusion[6]. Wayside signals are not used on the Shinkansen guideways, and the current-block signal is displayed on the dashboard. In 1995, JR East, which is one of the three national passenger rail operators and operates two of the four Shinkansen lines, began looking at how to best display the next block's signal as well. In their efforts to shorten the distance between trains[7], standardize in-cab displays, improve design and include information regarding the next block as well as the current block, JR East has done extensive testing involving surveys, simulations and overlays of information in cabs in actual operation. JR East feels that giving the engineer more than two blocks of information may be too much, as the engineer will not be able to use this information (Horiuchi 1996). Consequently

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wired analog ones used in older locomotives (even though the new ones will still be software-generated).

[6] Because engineers are certified by track, not by locomotive (similar to the certification process in the US) engineers may be presented with an unfamiliar cab on any trip. However, Shinkansen engineers must be specially certified to operate Shinkansen trains in general.

[7] The Shinkansen trains are among the fastest in the world; however, the JR operating companies are struggling to find a way to increase throughput with the conventional fixed-block control system that is currently being used there.

they have focused their efforts on how best to display the current- and next-block information needed to operate the train safely and efficiently.

The design they are leaning toward does not show any block signals at all. Rather, the display contains a circular speedometer with a triangle around the perimeter that indicates the maximum speed which will allow the operator to stop/decelerate the train in time for the next block. If the actual speed of the train is within a certain buffer range of this indicator, the signal turns yellow. If the actual speed surpasses the maximum safe speed, the signal becomes red and the emergency brake is activated. In addition to this speed control information, JR East has proposed a distance gauge that would show the distance (but not the signals) between the operating train and the next train down the track. They are still conducting tests into how the engineer will utilize this information.

France

The high-speed trains operated in France, the Train a Grande Vitesse (TGV), are operated partially on dedicated rights of way and partially on mixed-use guideways. The manufacturer of the TGV trainsets, GEC Alsthom, makes at least seven distinct models of trainsets for use in France by SNCF, with five of those being TGV trainsets. One of the TGV lines, the PBKA or "Thalys," travels to Brussels, Cologne and Amsterdam from Paris[8]. The non-TGV trainsets manufactured for use by SNCF are used for travel between Brussels and London. As a direct result of the differing operating environments, there are a number of different cab environments on the TGV trains. The older TGV trains (the Paris-Southeast, or PSE, which began operation in 1981; the Atlantique, or TGV-A, which began operation in 1988; and the Reseau, or TGV-R, which began operation in 1991) have a left-hand side operator's position, while the newer TGV trains (the 2N, or double-decker, and the PBKA, both of which began operation in 1995) have a central operator's position to accommodate travel on foreign tracks where the traffic and signals may be either on the right-hand (e.g., Germany) or the left-hand (e.g., France and Belgium) side (see Figure 2.5). The older trainsets used a wheel to control power output from the motors, while the newer trainsets have a more conventional traction lever. The newer cabs with the central

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[8] GEC Alsthom also makes a TGV-style train for Korea and a separate model for Spain.

operator's position have a much wider instrument panel area, necessary for the variety of signaling systems currently in use by the various European railways.

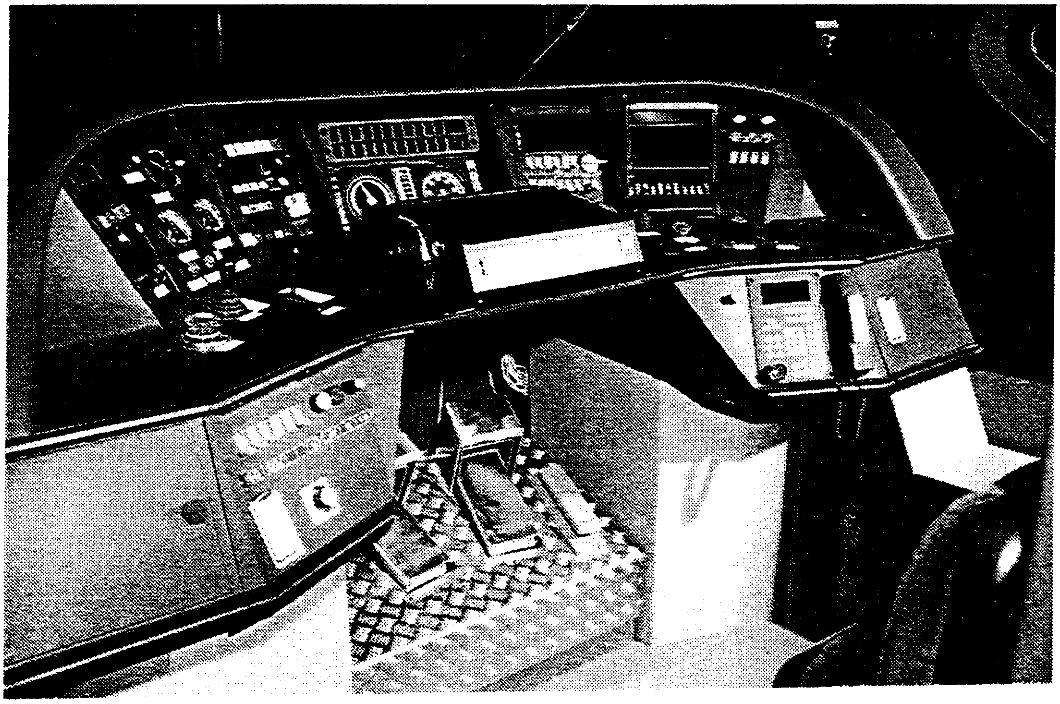

Figure 2.5: Interior of a TGV-PBKA Cab (courtesy of GEC-Alsthom)

Beginning with the TGV-A in 1988, TGV trainsets were equipped with an on-board data processing system which was used for running train start-up tests, displaying equipment status and running troubleshooting or repair procedures. The data processing system interface consists of a recessed monitor and keyboard located to the right of and behind the traction control lever or wheel (depending on the type of trainset). The system interface does not appear to be highly accessible, though it is not used very often at all.[9] Track-side signals are not used on the dedicated high-speed guideways, as all signaling is displayed in the cab. The cab signaling provides ten aspects. The engineer's control task is made somewhat simpler by the fact that each block is of a uniform length (2.1 km, or about 1-$^1/_3$ miles).

SNCF has experimented with a "moving-block" train control system, named ASTREE, in which

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[9] This is in contrast to the gauge (operating) and diagnostic displays of the Genesis II cabs, which are side-by-side directly in front of the engineer to provide equal access to each, despite the fact that the engineer rarely ever utilizes the diagnostic display during a normal trip.

the train's speed and location are calculated on-board and relayed to a central control area where the data is combined with those of other trains to calculate maximum safe (current) speeds. This project has been halted and the data gathered are being used to, in part, develop the European Train Control System (Jane's 1996). The Astree experiment focused more on the central control of the trains, rather than on the in-cab display of information to the operator. However, it does represent one of the more complete implementations of advanced train control and datalink communications to date. Though the in-cab display was somewhat crude, it did include such items as a target speed, an updated schedule, and suggestions for energy savings (see Figure 2.6).

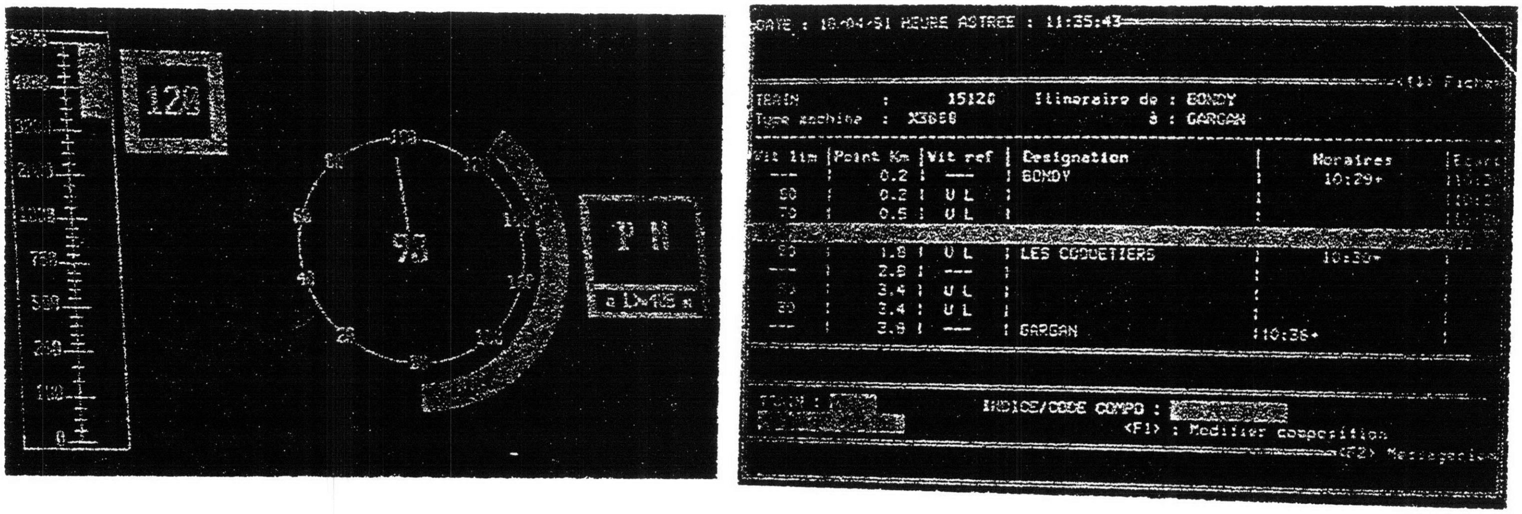

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Figure 2.6: Astree In-Cab Display (de Curzon 1994)

Germany

The German high-speed train system, the Inter-City Express (ICE), boasts the highest level of automation of any rail network, allowing manual control, manual selection of cruise control speed, and fully automated speed control (FRA 1991b). During manual control, the automatic train control system is still in effect. If the train reaches the nominal speed curve (i.e., that speed above which the train could not decelerate or stop in time for the next signal using service braking), a warning is given to the engineer; if the train reaches the monitored speed curve (i.e., that speed above which the train could not decelerate or stop in time using the emergency brakes), the emergency brakes are applied. Before each trip, the engineer must key in the train identification number, the train length and the status of the braking systems. During the trip, the operator must input any changes in the braking capability of the train to allow the ATC system to make the necessary calculations accurately.

The in-cab displays consist of two analog circular gauges for speed and power in the middle of the dashboard with an angled software-generated display on either side (see Figure 2.7); one monitor is for braking information, while the other displays general diagnostic information. The layout of the ICE particularly impressed several of the Amtrak design engineers during its recent tour of the United States.

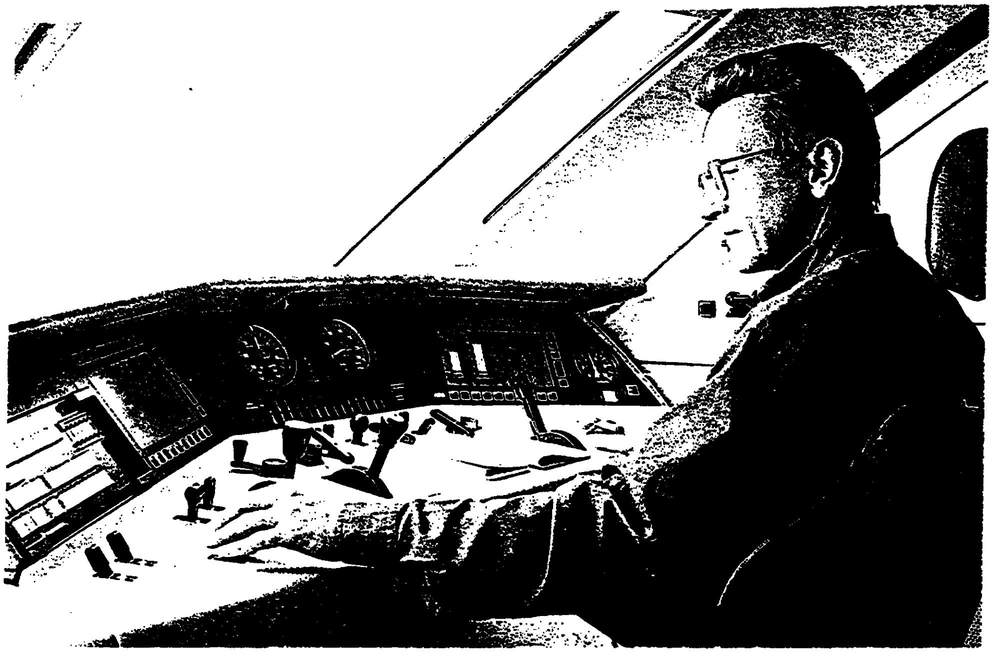

Figure 2.7: Interior of an ICE Cab (courtesy of DB)

In 1991, DB instituted a new signaling scheme wherein the wayside signal displays the aspect, the effective speed limit (in multiples of 10 km/hr) and the direction of divergence if approaching an interlocking. The signal indicates the status two blocks ahead of the train (Jane's 1996). Thus, the engineer is given greater time in which to react without any more information having been transmitted. However, the disadvantage to the train company is the longer headways (and thus, lower throughput) that result.

DB began testing in 1995 of a high-capacity train control scheme based on fixed-block track. CIR-ELKE (Computer Integrated Railroading: Erhohung der Leistungsfahigkeit im Kernnetz) utilizes shorter block lengths than are currently used and approaches a moving-block system of sorts. Based on current train positions and speeds, a central computer calculates minimum acceptable headways, which are then relayed to the cab of each respective train. No wayside signals are used.

AAR

ATCS

AAR, along with RAC, twelve years ago developed a comprehensive set of so-called Advanced Train Control Systems (ATCS) guidelines outlining their vision for "a system using digital data communications and computers to manage and control the dispersed elements of the railroad, [from] locomotives, track forces, and field devices to the dispatch office and railroad management systems (Moody 1993)," a system AAR felt would improve safety, efficiency and customer service. These specifications have been updated and revised several times since, and several railroads have implemented test beds of ATCS-style systems in various forms (Moody 1990; Progressive Railroading 1991). Some recent tests of ATCS-style systems including AAR's system on the Chicago-St. Louis line, GE's system on Burlington Northern-Santa Fe and Union Pacific lines in the Northwest, and the Incremental Train Control System developed by Amtrak and Harmon Industries in Michigan (Jane's 1996).

However, ATCS as a whole has not yet gained industry-wide acceptance, due in no small part to the huge price tag associated with implementing such an all-encompassing system. Early FRA estimates indicated that mandatory ATCS would cost between $8 billion and $16 billion, while skeptics claim that the benefits—such as increased throughput and reduced risk of collision—are difficult to substantiate (Welty 1993). The Advanced Railroad Electronic System (ARES) was an ATCS-style system developed by Burlington Northern Railroad (BN) in conjunction with Rockwell International that got its start in 1981. ARES was a particularly ambitious train control project, encompassing automated traffic planning and assessment, computerized dispatching and record keeping, in-cab command and control, improved data links, automatic location and speed monitoring, and locomotive health and status monitoring (Moody 1990). BN struggled with the estimated cost of the system ($350 million in 1991, compared with 1989 revenues of $4,606 million and net income of $242 million) vis-à-vis projected returns and the uncertainty of those returns (HBS 1991). BN has since turned the rights to ARES over to Rockwell and is currently testing a competing train control system in the Pacific Northwest that is a joint project with GE.

ATCS Guidelines

The ATCS guidelines provide for automatic oversight of train control using a communications-based, or “moving block,” system, such as the program SNCF has tested in France (ASTREE, described above). In the ATCS scenario, though the computer can override any user input that would result in an unsafe situation, the human operator is nominally in control of the train. The ATCS specifications outline two types of cab displays—track/movement authority (and train control information (LSI display, graphical—see Figure 2.8; and ATCS display, text or graphics—see Figure 2.9)—that some freight companies have begun implementing.

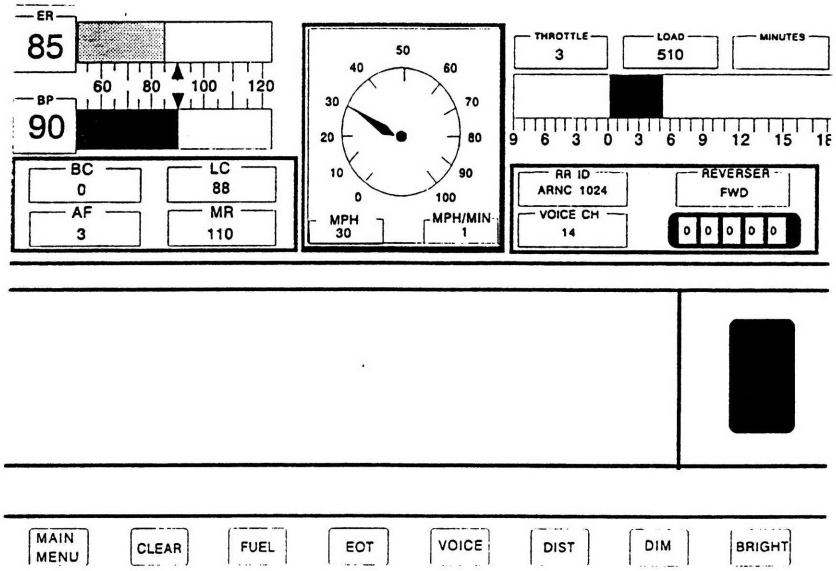

Figure 2.8: AAR LSI (Train Control) Display (courtesy of AAR)

These guidelines (which are not requirements, but rather suggestions) designate what types of information are required to be displayed (such as brake pressure, speed and acceleration, throttle/brake position, load (amps), train ID, voice channel, train signal aspect, function keys, alarm block) and what information is optional (such as ATCS information, track information, preview/prediction information, individual motor current, etc.), based on various focus groups and input from administrators, engineers and manufacturers. The guidelines go on to discuss generally how these pieces of information should appear on the screen (see Figures 2.8 and 2.9). The train control display sets very clearly where each piece of information should appear on the screen and delineates an area for "optional" information (such as control notices or the track authority display information in the case of a secondary display failure), ensuring fairly easily interoperability. The track authority display on the other hand is clearly at an early developmental stage, in that the display is allowed to be either graphical or text based, leading to two extremely different interfaces. The suggested graphical track display incorporates many of the same concepts encompassed by Askey's preview, predictor and advisor displays (e.g., track preview, prediction of train location and speed 60 seconds in the future, visual/auditory cue of when braking should be initiated).

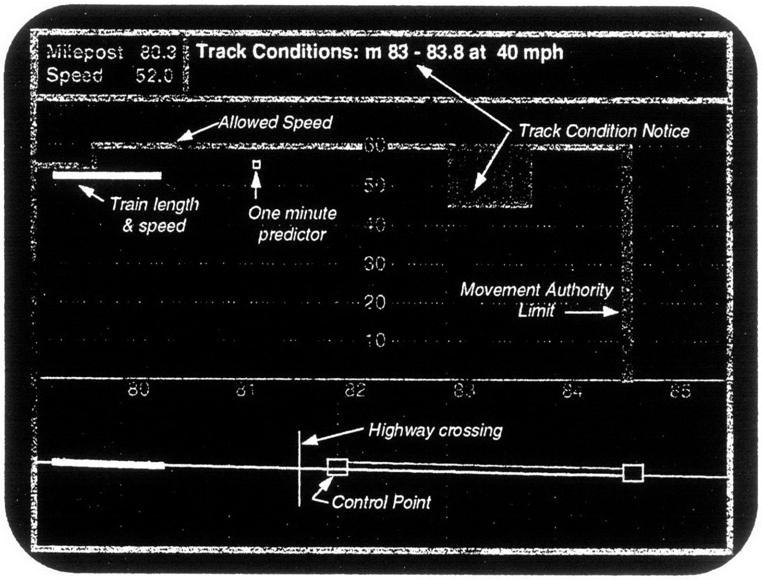

Figure 2.9: AAR ATCS (Track/Authority) Display (courtesy of AAR)

As indicated above, tests performed at IITRI have shown increased safety and efficiency of train operation when the ATCS display is used rather than the paper warrants traditionally used (Kuehn 1992). These results show the promise of such decision aids. However, these guidelines were intended mainly for freight trains—according to the AAR, Amtrak chose to have very little involvement in the development process, and the only concession Amtrak requested was to allow the speedometer to reach 160 mph instead of the proposed 100 mph. The lack of involvement on Amtrak's part in the development of the ATCS specifications begs the question of how the guidelines might differ had passenger operation been given more weight.

Amtrak

The migration to high-speed rail in this country has been a slow one consisting of incremental increases in allowed maximum safe operating speeds (in the form of waivers to surpass the national speed limit) since the national 79 mph speed limit was initiated in 1947. Currently, the highest waiver is for Amtrak's Metroliner which travels between Washington, DC and New York. However, to travel above 79 mph, a train must be equipped with in-cab signaling and automatic train protection (ATP), logic that will initiate emergency braking if the speed limit is violated.

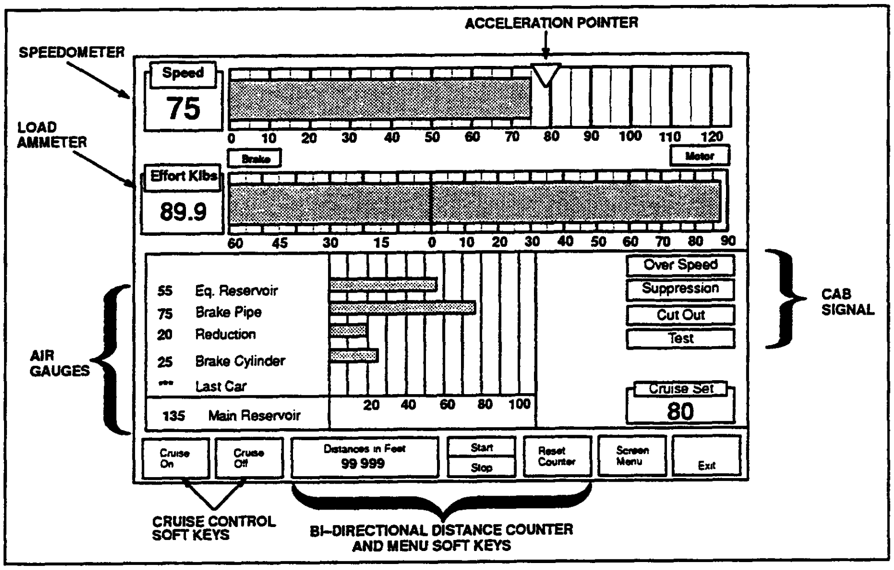

Figure 2.10: GE/Amtrak Genesis II Gauge Display (courtesy of Amtrak)

The Genesis Series II cabs, put into operation in 1995, marked the first software-generated displays used on passenger train locomotives in this country; as all previous locomotives had utilized hard-wired analog displays. The layout of the Genesis cab in general was quite a departure from previous locomotives, with the addition of a desk area and three computer display screens (two for the engineer, and one for the assistant). The auxiliary function display is quite complex, with several menu-driven levels that can be selected, though the gauge display (Figure 2.10) is the display the engineers use most often in routine train control. The engineers I spoke with did not use the triangular "future speed indicator" above the speedometer. The general response to both the cab and the display was positive, and Amtrak plans to continue with software-generated displays in the future, though some engineers felt that the Series II displays were too "busy," and many felt that a circular speedometer (like the traditional circular analog gauges) would be better.

Amtrak received 30 new P4250 locomotives in 1996 from GE, which basically amount to Genesis "Series III" locomotives as they will be very similar to the P40-DC (or Series I) and P32-AC (or Series II) Genesis locomotives. Amtrak has contracted for 26 trainsets to be manufactured by Bombardier for the North-East Corridor. These trains, dubbed "American Flyer," will be rated for service at 150 mph. Amtrak has also developed a new set of signals with nine aspects to handle the finer gradations of speed control required at these higher speeds.

Summary

There is a wide variety of in-cab display paradigms in use in the various countries operating trains at high speeds. The differences that exist relate to almost all aspects of train control and in-cab displays and aids—which pieces of information are provided (e.g., fault indication lights), the level or amount of each piece of information provided (e.g., one block or two blocks of signals), as well as how this information is laid out or otherwise displayed. For instance, Japanese engineers seem to favor linear speedometers, while American engineers seem to favor circular speedometers. Sweden presents the operator with the current- and next-block signals, while Japan and the United States only display the current-block signal, and Japan is considering not displaying any signal at all (only the maximum safe current speed). Japan and Germany do not offer the redundancy of wayside signals on high-speed track lines, while the United States and Sweden do (both of those countries operating on mixed-use guideways).

All the surveyed countries have ATP to the extent that trains that violate the current block speed limit are automatically braked. France and the United States each have a separate dedicated diagnostic display, though the French version is much less accessible than the American version. Furthermore, the American (Amtrak) display discussed here is just one of the many in use on America's higher-speed tracks. Japan and the U.S. have software-generated operating displays, while France and Sweden rely on hard-wired gauges and lights to display most train-control information; Germany offers a curious combination of traditional analog circular gauges for speed and power and modern software-generated displays for brake and schedule information which has attracted some amount of praise.

Though the variety of in-cab display conventions makes it difficult to choose one particular research direction, it does highlight the need for further examination of display conventions. Particularly, each country has its own convention regarding how control information (speed, traction and braking) is displayed. To what extent does the way control information is displayed (e.g., horizontal vs. vertical, linear vs. circular, etc.) affect how the engineer is able to operate the train? Furthermore, there is even much variation within individual countries' and individual operators' territory, with respect to signaling paradigms and display regimes. This variation has the potential to be quite dangerous, as it can cause confusion among engineers who may have to operate a different locomotive (with different displays) on any given day. A uniform signaling system and as uniform a cab environment as possible would increase safety by reducing confusion and minimizing operator errors.

There also seems to be consensus among the rail operators in the various countries operating trains at high speeds that the engineer needs some information over and above the current-block signal, particularly if travel speeds are upwards of 150 mph, though nowhere is an engineer given any information about a distance further ahead than the next block. The IITRI ATCS results seem to indicate that preview information is helpful not only for safety, but for efficiency as well,[10] and Askey's study backs up that view. This research seeks to build on this knowledge regarding "preview information" by specifically examining the length of preview as the independent variable.

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[10] The IITRI experiments included a "dummy" display with the written authorities to be sure that the results were not obtained from simply having any display at all.

III: Experiment

Overview

The purpose of these experiments was to gain insight into the information that is needed by train engineers to operate the train as safely and efficiently as possible. With train speeds in the United States rising to 150 mph by the end of the century, there is an increased focus on the potential problems inherent with high-speed train travel. A problem that poses a particular hazard is that train engineers have less time to incorporate and analyze the same amount of information (e.g., wayside signals, temporary speed restrictions, etc.). A potential solution to this problem is to give the engineer information about the status of the track some distance ahead of the train, thereby allowing the engineer more time to react to a change in status or an unexpected scenario. We have developed one type of display that provides authority and traffic preview (speed/authority restrictions, other traffic, obstructions, etc.) to the engineer, as well as advanced train control information, in a format based heavily on (Askey 1995). The questions we have examined relate to whether or not preview information improves safety and efficiency of train operation, and, if so, how much preview information (i.e., how far ahead of the train the engineer is given information regarding the status of the track) is useful.[11]

Engineers' Information Needs

In countries in which the high-speed trains operate on separate guideways, the information requirements faced by engineers of high-speed trains may differ significantly from those faced by engineers of lower-speed commuter trains. For instance, an engineer of a high-speed train on an isolated guideway may rely heavily on knowing the upcoming authorities, whereas an engineer of a commuter train on a mixed-use guideway may rely more on knowing the locations (and directed velocities) of other nearby trains. In this country, it is not feasible to have high-speed trains travel on isolated guideways; thus there is necessarily a larger intersection between the information needs of high-speed and commuter engineers. Information that is helpful to the engineer may include upcoming speed/authority restrictions, location and velocity of nearby

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[11] We have focused this experiment on how much information to present, rather than on improving the presentation of the information.

traffic, and upcoming distance cues (such as mileposts) that may aid with direct train control.

We have tried to incorporate these pieces of data into a display that is easily integrated into the engineer's control loop. In this experiment, we compared this display to the Genesis II display, developed by Amtrak in conjunction with GE and put into use in 1995.[12] The Genesis II display offers a replica of the wayside signals in the cab, but does not provide any sort of preview information.[13] The experiments described in this chapter have sought to examine the differences in safety and efficiency of train operation that might arise by using these two different types of displays.

To investigate these questions, we ran human-in-the-loop experiments on the MIT/Volpe train simulator, using professional rail engineers and MIT students as subjects. Using both groups of subjects allowed us to have more data points, make comparisons between the two subject groups, and correlate data from previous studies done on the simulator using only MIT students as subjects.[14] During each subject's operation of the simulator, we collected data on the train's speed, the signal settings, the schedule deviation and the station-stopping accuracy; in this way, we were able to compare the speed control, signal adherence, schedule deviation, and station-stopping accuracy across the different displays we used, given various "disturbances," or unexpected scenarios.

MIT/Volpe Train Simulator

The simulator itself consists of a local network of three Silicon Graphics workstations and one Windows-based PC. The simulator can handle many "trains" operating at once, though each train requires two workstations to operate. When driving the train, the subject sits in a simulated locomotive cab, which includes a desktop containing a 17-inch display monitor, one control stand on either side of the monitor, and a windshield through which the subject views a

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[12] The Genesis II display was Amtrak's first software-generated display.

[13] The software-generated display does contain a 60-second speed predictor. However, this function was not replicated in these experiments due to its spurious behavior and lack of use by engineers.

[14] The length and structure of the training provided to each of the two subject groups was different and is discussed below.

projection of the out-the-window (OTW) view on a 6-foot by 4-foot screen. The situational involvement of the subject is enhanced by two-way radio communication with the central traffic controller (CTC), and track/engine noises tied to the simulation and broadcast via speakers in the cab (see Figure 3.1 for a snapshot of the cabin environment). The two in-cab control stands govern the emergency brake, doors, cruise control, alerter, overspeed warnings, bell, horn and circuit breakers. A separate workstation functions as the CTC's control station, allowing the CTC to control all the switches and authorities. In these experiments, the author performed the duties of the CTC. See (Lanzilotta 1996) and (Askey 1995) for further descriptions of the M.I.T./Volpe train simulator.

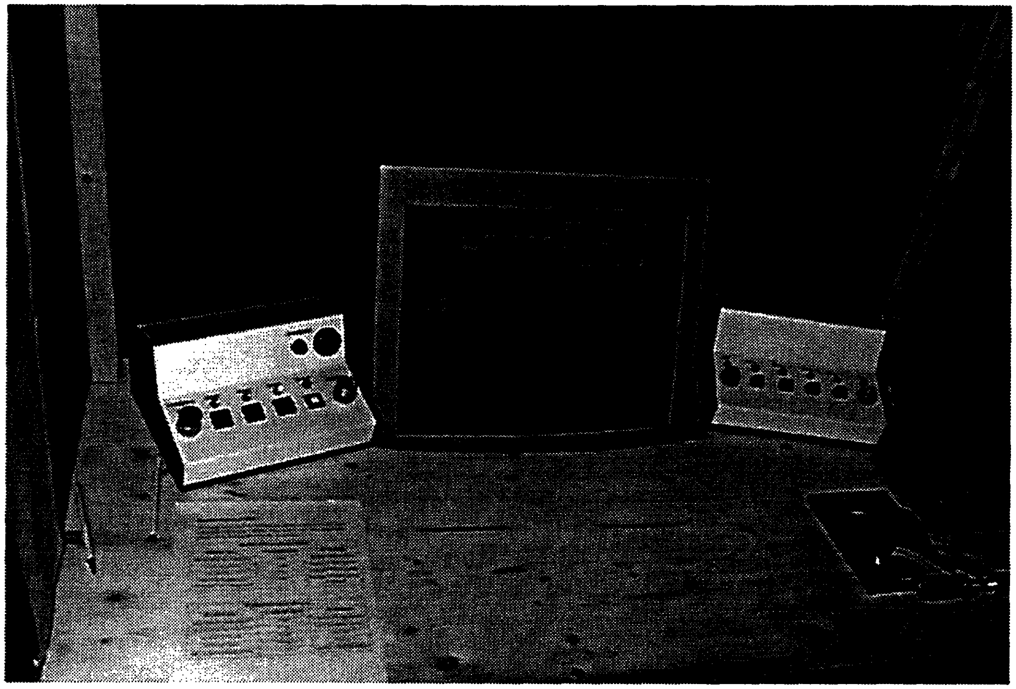

Figure 3.1: Simulated Locomotive Cab

Experimental Design

Independent Variable: Preview Distance

The independent variable that was manipulated was preview distance. Throughout the experiments, we used two different types of displays to accomplish the different preview distances. The baseline display was a mock-up of the Genesis II display (see Figure 3.2), the most recently-designed display Amtrak has in operation; the locomotive cabs in which this display is used show only the current block signal (i.e., no preview information) in the form of a location-coded signal and digital readouts of the civil and signal speed limits (to the left of the display in Figure 3.2). The other displays used were all variations of one display that shows the same brake, traction and warning information as the Genesis II display, but also contains distance-speed and distance-distance sub-displays (see Figure 3.3).

As the preview displays incorporate extra information in addition to the basic train control included in the Genesis-style display, they necessarily had to be configured differently. The large area in the middle of the preview display is a preview of the upcoming speed restrictions for the track on which the train has authority to move. The horizontal axis scales with distance, while the vertical axis scales with speed. The vertical white line in this portion of the display indicates the current train position, while the short horizontal white line emanating from the vertical white line indicates the train's length as well as its speed (as it moves up and down the vertical axis). The horizontal and vertical red lines indicate the maximum allowable speed at that location, taking both civil and signal limits into account. If the white horizontal bar indicating the train's current location is ever above the red lines, the train is violating the effective speed limit. Mileposts, switches and stations are indicated just below the speed preview sub-display, above the track preview sub-display (described below).

In addition to providing preview information regarding upcoming speed limits, the preview displays also provided advanced train control information in the form of predictive full-service and emergency braking curves.[15] The yellow curve between the train's current location/speed and 0 mph some distance in front of the train indicates the trajectory (in distance-speed space) the train will follow if a full-service application of the brakes is provided. The red curve between the train's current location/speed and 0 mph some (shorter) distance in front of the train indicates the trajectory the train will follow if the emergency brakes are applied. The green arc emanating from the train's current location/speed is a prediction of the trajectory the train will follow in the coming 25 seconds given current grades and control input—as the amount of thrust or braking is changed, the predicted trajectory will change accordingly.

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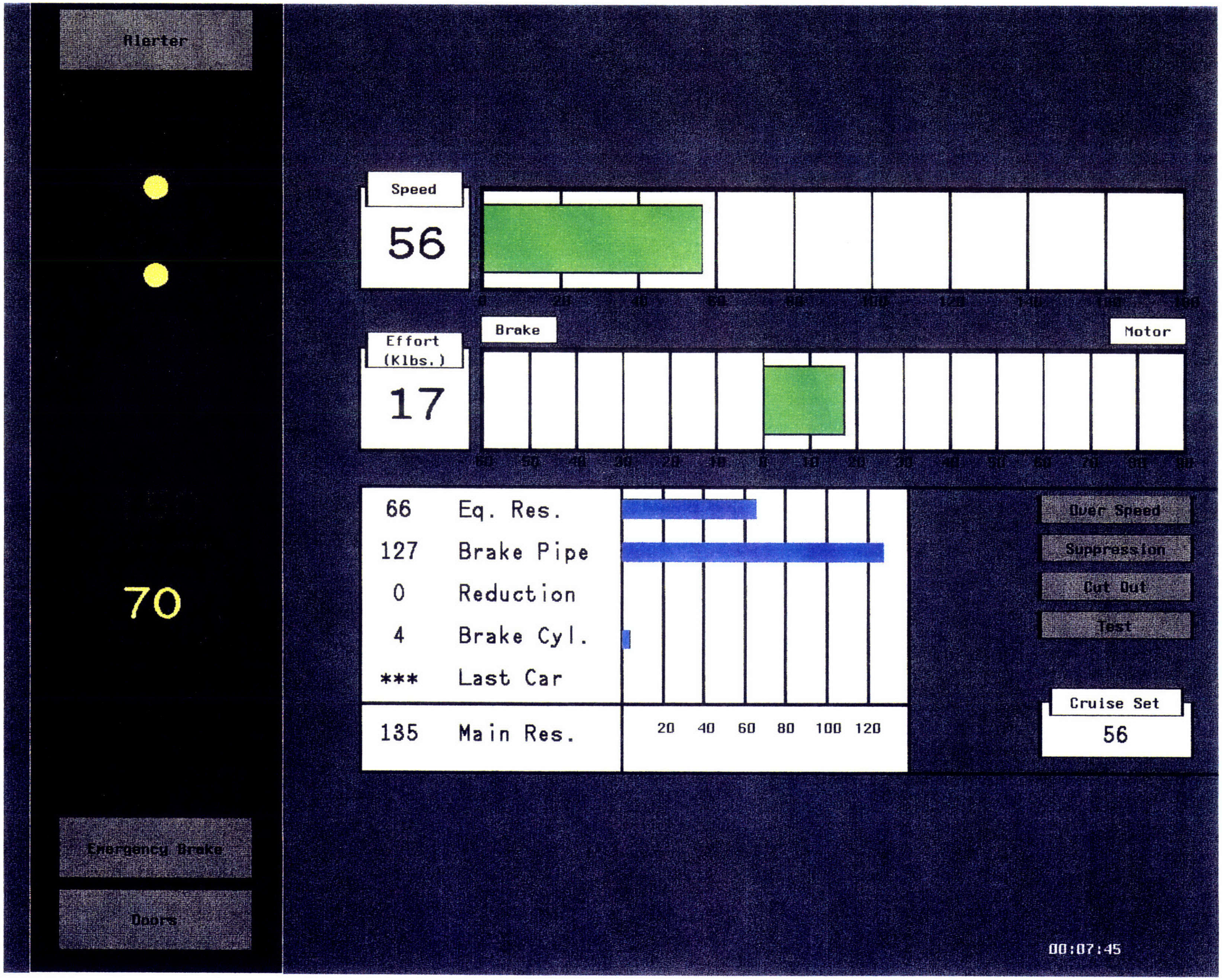
[15] (Askey 1995) showed the advantages of providing this control information along-side the preview information.



70

Speed 56

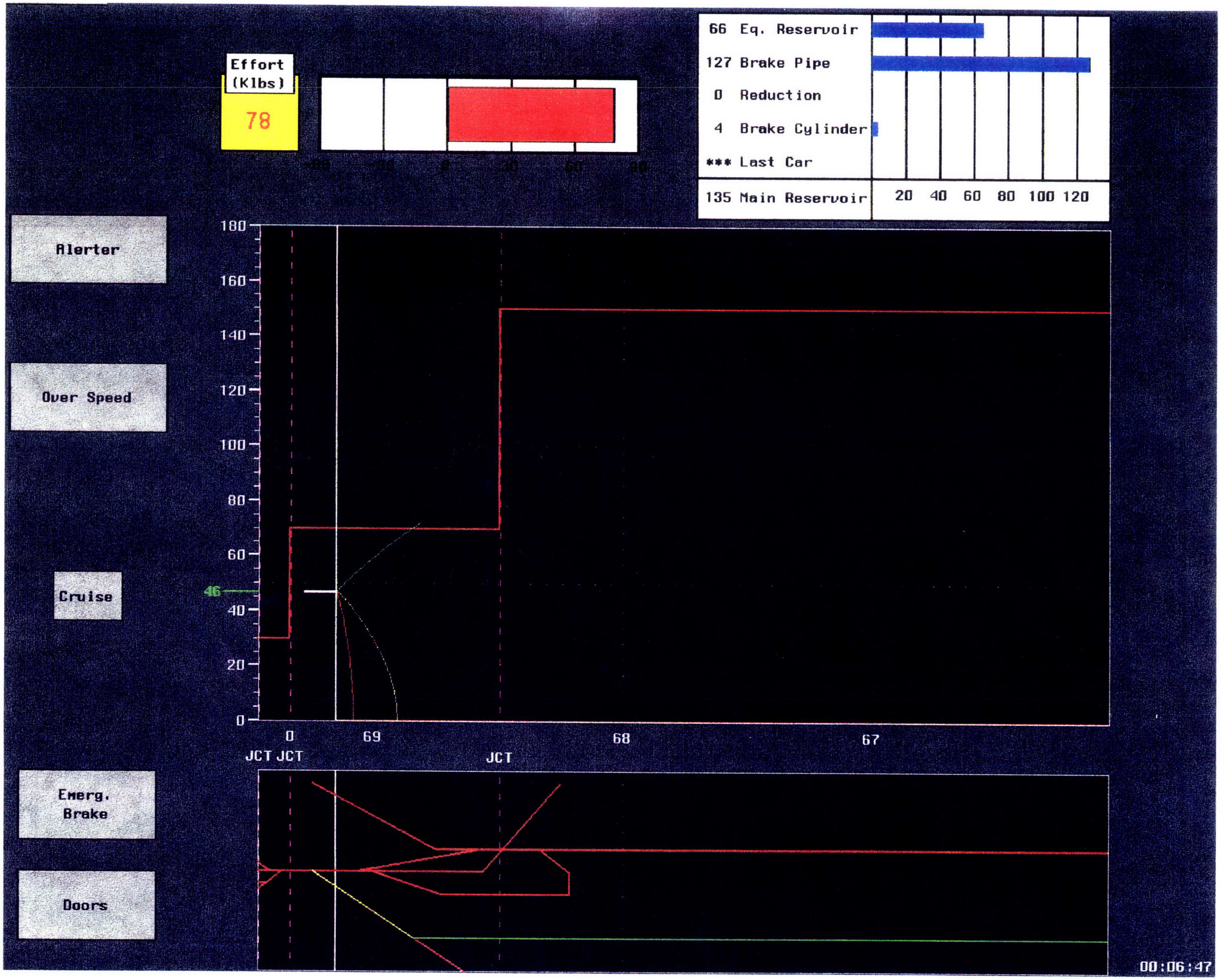
Effort (Klbs.) 17

66 Eq. Res.
127 Brake Pipe
0 Reduction
4 Brake Cyl.
*** Last Car
135 Main Res.

Cruise Set 56

00:07:45

Figure 3.2: Adaptation of Genesis II Display (developed by GE and Amtrak)



66 Eq. Reservoir
127 Brake Pipe
0 Reduction
4 Brake Cylinder
*** Last Car
135 Main Reservoir

Figure 3.3: Preview Display

The smaller display below the speed preview sub-display is a preview of the upcoming track structure and authorities. Green indicates authority to move in that portion of track, while red indicates a lack of authority. The horizontal (distance) axis is on the same scale as the speed preview sub-display, and the same milepost, switch and station indications apply.

We controlled the independent variable (preview distance) on these displays by varying the resolution of the horizontal (distance) axis on the speed and traffic preview sub-displays to control how far down the track the operator can "see." One hypothesis was that stopping distance is the most influential factor when considering how far down the track the engineer needs to be able to see; thus, one preview distance was a function of stopping distance at full-service braking (which is only a function of speed and up-coming terrain, once a model of the train dynamics is known by the on-board logic) and "reaction plus decision" distance (approximately reaction time plus "decision time" multiplied by current speed, ignoring acceleration during that same time period)—as the train's speed increased, the preview distance provided to the engineer increased accordingly, always providing the status of the track at least some distance ahead of the end of the full-service braking predictive curve (i.e., the resolution of the horizontal axis decreased, as the display provided information about the status of the track further ahead of the train's current location). This "variable preview" display had 500 m as the minimum preview offered at low speeds. The other (fixed) preview distances (see Table 3.1) were zero (the baseline Genesis-style display described below), 1.4 miles (approximately two blocks, mimicking the level of information now available in Sweden), and 3.4 miles (which is higher than the longest variable preview distance expected at the top speed of 150 mph).[16] Each of the preview displays shows the track 500 m behind the train as well.

Current block only	~1.4 miles ahead	~3.5 miles ahead	Variable
(Genesis-style display)	(current and next block)	(current and about three blocks)	(function of stopping distance and reaction time)

Table 3.1: Independent Variable (Preview Distance) Options

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[16] As part of our post-experiment debriefing, we asked each subject which preview distance they (subjectively) preferred, and which made their job easiest. It would be interesting, as part of a possible future experiment, to give the engineers one trip at the end of the experiment, in which they can set the preview distance themselves. This would allow an analysis of engineers' subjective information needs in a relatively uncontrolled environment.

Dependent Variables

We were interested in the effect of these displays (and, more specifically, of the varying preview distances) on safety and efficiency of train operation. The prevailing measure of train safety among the public is the frequency of collisions or derailments. However, accidents happen so infrequently that they are hard to predict (and difficult to "provoke" within a simulation); thus, train operators are not—and can not—be judged based on this metric, as that might promote a relatively cavalier attitude among operators given the relative paucity of accidents. A train operator's safety record is determined in part based on his or her adherence to the signals and speed limits—this adherence is indicative of the operator's ability to maintain control of the train and obey the authorities set either by the CTC or automatically by the system. Furthermore, the operator may have full control of the train but be unaware that action is needed—we can get an idea of how aware the operator is of his/her surroundings by measuring the operator's reactions to various unexpected events. And finally, the passenger rail company is not interested only in safety—the train operator must get the passengers from station to station in a timely manner, according to the schedule, and stop at the station in a controlled, predictable manner. Thus the five metrics of interest, relative to safety and efficiency of train operation, that were monitored and compared in this experiment were: (1) speed control, (2) signal adherence (obeying authorities), (3) reaction to unexpected scenarios, (4) deviation from the dictated schedule, and (5) station-stopping accuracy. These general metrics of safety and efficiency are described in greater detail below, in the form of the specific dependent variables we have measured in our experiments. Another metric on which engineers could be evaluated, but was not used in this study, is force exerted on the train during acceleration or deceleration (i.e., a passenger comfort index).

Speed Control

Speed control is automatically monitored by collecting data on the train speed relative to the allowed speed. Train engineers are expected to keep their trains within a certain range of acceptable values. An overspeed may result in an automatic penalty application of the brakes (on properly-equipped trains on certain tracks), while a severe underspeed will complicate the dispatcher's job, waste energy and cause unacceptable schedule deviance. We monitor the train's speed at regular intervals, and look at the magnitude of each transgression above the limit.

The operator is allowed to drive up to four mph above the speed limit indefinitely.[17] If the train is operated at a speed greater than four mph over the limit for more than five seconds with no application of the brake, a penalty application of the full-service brakes is initiated by the train's automatic train protection (ATP) system; control of the train is not returned to the operator until the train's speed is brought below the limit. The simulator automatically records the duration of any overspeed, as well as the number of penalty brake applications.

Signal Adherence

A task similar to speed control is signal adherence. Strictly speaking, an authority overrun (i.e., running past a red "stop" signal) or a missed signal (i.e., passing a signal at a speed higher than indicated by the signal) is an overspeed violation (i.e., the train speed is greater than the speed limit). Though the outputs (engineer actions) of these two control tasks are similar, the inputs and decision processes are quite different. When controlling the speed under a constant speed limit, the engineer must decide based on the operating conditions whether to apply the throttle or the brake; when adhering to an (upcoming) signal change, the engineer must decide at what point to apply the brakes. In the former (i.e., speed control) case, the engineer risks overshooting or undershooting the target speed—at most, the initial overshoot will be just greater than zero, as the train must first cross the speed limit before surpassing it. In contrast, in the latter (i.e., signal adherence) case, the engineer is at risk of severely overshooting the upcoming signal if the brakes are not applied in time; that is, the initial overspeed could be significant relative to the new speed limit. We measured signal adherence by the number of signal overruns (i.e., entering a block with a speed greater than that block's limit) and the magnitude of each.

Reactions

Reaction to failure scenarios or immediate (i.e., current-block) signal changes can be monitored by collecting data on reaction times and "reaction distances" (i.e., the distance between the train and the stimulus, if the stimulus is an external one such as a signal or a car stuck in a crossing). The time of the stimulus is automatically recorded in the data log; if the response falls within the

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[17] The amount of this "buffer" zone varies from train to train, and track to track. It can be as little as zero mph and as much as ten mph.

domain of predictable actions, it too is recorded. The reaction time is simply the time between the stimulus and the response, while the reaction distance is the distance between the stimulus and the train at the time of the response. The reaction time gives us insight into how vigilant and aware the subject is, while reaction distance gives us insight into how costly the reaction time is in terms of distance traveled. As was alluded to earlier, it is the reaction distance that is severely cut short as train speeds increase, while reaction times are ostensibly constant for a given operator in a given environment (i.e., a control input performed after the same reaction time has elapsed will be performed at a distance farther from the stimulus at higher speeds). Of course, there are some situations (e.g., a signal change many miles down the track) that don't necessitate immediate reaction; however, there are many situations where reaction distance will be critical.

Schedule Deviation

Schedule deviation is the difference between the expected arrival time at each station and the actual arrival time at each station. This is an important measure of performance, as customer satisfaction is critical to the growth of rail travel in this country. Furthermore, schedule deviation complicates the dispatcher's job and could result in a domino effect of further deviations for other trains, given the constraints of limited track space.

Another measure of efficiency of operation, which should be considered for future experiments, could be overall trip cost. Though many factors enter into the "cost" of a trip, a metric that scales with cost could be arrived at by measuring how much energy was consumed by the train and add to this a weighted penalty based on schedule deviation. However, it may be difficult to train the engineer to understand the relative weights one has assigned to schedule deviation and energy consumption or to assess the engineer's intentions while operating the train.[18]

Station-Stopping Accuracy

Station-stopping accuracy is important for two reasons. In terms of our simulation and training

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[18] It would be interesting, perhaps as a separate experiment, to assess the engineers' cost functions regarding ride comfort, energy consumption and schedule adherence vis-à-vis the analogous cost function of the part of the rail operators [see Patrick, 1996].

procedures, accurate station-stopping demonstrates an understanding of the simulator and control of the train that is necessary to perform properly in other aspects of the simulation. Furthermore, in actual train operation, accurate station-stopping is an important part of the engineer's job, as an inaccurate stop would require the conductors to do extra work and may force the passengers to lug their bags to different exits. In this research, we measured the subjects' actual stopping location at each station relative to a pre-defined mark (the end of each platform).

Task

Each subject operated the MIT/Volpe train simulator through a particular section of track which mimics a commuter ride from South Station in Boston to Attleboro through two intermediary stations (Sharon and Foxboro). The time for a "normal" trip between each station is approximately twelve minutes on average, bringing the total travel time on such a trip to approximately 37 minutes, including station stops. The engineer's task was to control the train, given the schedule constraints and whatever the operating conditions happen to be, while the simulation recorded their ability to perform this task (by observing the dependent variables noted above) given the various disturbances. These disturbances included: Having to take a siding/parallel track due to an unexpected train coming in the opposite direction, an unexpected change to a restricted signal ("stop") with some warning (possibly due to a car stuck in a grade crossing that has been reported to the CTC), an unexpected change to a restricted signal ("stop") with little warning (possibly due to a relay failure or some other "invisible" trigger), and some static temporary speed restriction ("stop"—possibly due to a maintenance crew in the right of way). During each trip between Boston and Attleboro, each subject actually traveled three legs (i.e., from Boston to Sharon, from Sharon to Foxboro and from Foxboro to Attleboro); on each Boston-Attleboro trip, the subject encountered disturbances in two of these three legs.

With four different "values" for our independent variable (i.e., zero preview, variable preview, 1.4 miles and 3.5 miles) and two disturbances per trip, each subject ran one trip with each display and saw eight disturbances—two on each display. With four different types of disturbances, each subject saw each type of disturbance twice. Thus, each subject's experimental session consisted of four Boston-Attleboro trips (two round-trips total), each trip under a different in-cab display.

The experiment was designed to use six Amtrak engineers participated as subjects.[19] An identical set of experiments was run concurrently, using six MIT students as subjects. Each of the six subjects saw four displays with two disturbances in each display, for a total of 48 data points for each subject group. [20] The disturbances were distributed among the displays and subjects, to counterbalance against learning and other biases, as shown in Tables 3.2 and 3.3:

Subject	No preview	1.4 mile Preview	3.5-mile Preview	Variable Preview
1	1, 3	2, 4	2, 3	1, 4
2	3, 4	1, 2	1, 3	2, 4
3	2, 3	1, 4	3, 4	1, 2
4	1, 2	3, 4	1, 4	2, 3
5	2, 4	1, 3	1, 2	3, 4
6	1, 4	2, 3	2, 4	1, 3

Table 3.2: Counterbalancing of disturbances across subjects and displays

Subject	Bos-Att 1	Att-Bos 1	Bos-Att 2	Att-Bos 2
1	No Preview	Short Preview	Long Preview	Variable Preview
2	Variable Preview	Long Preview	Short Preview	No Preview
3	Short Preview	Long Preview	Variable Preview	No Preview
4	Variable Preview	No Preview	Short Preview	Long Preview
5	No Preview	Variable Preview	Long Preview	Short Preview
6	Long Preview	Short Preview	No Preview	Variable Preview

Table 3.3: Order in which subjects saw each display

These data points are distributed among sixteen cells (i.e., disturbance X under display Y) as

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[19] An additional (seventh) Amtrak engineer participated. He was the first engineer to use the simulator, and the amount of feedback we got from him was so great that we ending up using him as a pilot subject so we could incorporate his suggestions before running experimental subjects. Only three of the six scheduled engineers were run; see the end of this chapter for more information.

[20] An unexpected signal change every 25 minutes or so is probably much too frequent, but the logistics of running a

shown in Table 3.4:

Disturbance	No preview	1.4 mile Preview	3.5-mile Preview	Variable Preview
1	1, 4, 6	2, 3, 5	2, 4, 5	1, 3, 6
2	3, 4, 5	1, 2, 6	1, 5, 6	2, 3, 4
3	1, 2, 3	4, 5, 6	1, 2, 3	4, 5, 6
4	2, 5, 6	1, 3, 4	3, 4, 6	1, 2, 5

Table 3.4: Distribution of data points (by subject number) among disturbance-display cells

Not all 48 data points were collected, for reasons described in the next chapter. In addition to our data, we gathered post-experimental qualitative feedback (by way of questionnaires and brief interviews) that aided us in making qualitative claims about the effectiveness of each display, both within each subject group and between the subject groups.

Subject Training

Due to the two subject groups' widely varying experience with train control (greater for the engineers) and computer environments (greater for the MIT subjects), the training regimens were different for the two groups. Training procedures for MIT students were developed during the previous two experiments using the MIT/Volpe train simulator (Askey 1995; Lanzilotta 1996), and I have relied heavily on the procedures developed by Lanzilotta.

MIT Students

Each subject was given a written tutorial of train control and simulator operation issues (see Appendix A) before arriving for the first session. At the beginning of the first session, after reviewing the material, the subject was asked to answer 25 multiple choice questions (see Appendix B), which the experimenter corrected and reviewed with the subject. After going over any incorrect answers and answering any questions at this point, the instructor led the subject through one trip between South Station and Attleboro (approximately one hour), utilizing each of

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significant number of subjects at a reasonable cost, in terms of both time and money, dictated such a scenario.

the displays to be used throughout the course of the experiment. The instructor demonstrated the control modes available to the operator, the communication with the CTC, and the meaning of each piece of data displayed, while the subject was given the chance to ask any questions he/she might have regarding the control of the train or the meaning of the information displayed.

When all questions to this point had been answered, the subject operated the train on five trips (approximately four hours) between Boston and Attleboro—the first leg with no disturbances, the next four with at least one of each of the disturbances.

Engineers

Though the rail engineers used as subjects each had extensive experience operating actual locomotives, we still had to spend a significant amount of time training them to use our simulator and particularly its operator interface. Though one of the experimental displays was similar to one of the interfaces they may have used (the Genesis display), the preview displays were unfamiliar, as was the type of information displayed on the advanced displays, the input controls, and the out-the-window view. Furthermore, the engineers may not have had experience with the Genesis II displays. The rail engineers were given a shorter version of the written tutorial given to the MIT students, though they were not quizzed on this material—instead, they were given an opportunity to review it with the experimenter and ask any questions they might have had.

We were able to arrange to bring in each engineer for one full day of experiments, and we planned the day so as to complete the training and all the experimental runs in that time-frame. The engineers' training sessions were similar to the MIT students', in that they consisted of an instructional portion and a test portion. The instructional portion, in which the subject was exposed to each of the displays and each of the disturbances while being talked through the operation of the train by the instructor, lasted one hour (i.e., one trip from Boston to Attleboro). After having the opportunity to ask any questions he/she might have, the subject then had three trips (approximately two-and-a-half hours) with disturbances to become familiar with train operation. At the conclusion of this trip, the formal training was done.

Conclusion of Training: Both Subject Groups

Training for previous experiments' subjects, all of whom were MIT students with no rail experience, varied in length from under three hours to six hours. Lanzilotta found that after three hours, his subjects were still learning how to operate the train effectively. To be sure that the subject had learned how to control the train effectively, the subject's performance with respect to schedule adherence, station-stopping, signal adherence and speed control were monitored on the final leg of their training trip. If the subject could not perform to an acceptable level, he or she would not have been permitted to continue with the experiments (though this did not occur for any subjects in this round of experiments). If the subject consistently performed to an acceptable level by the end of the second full round-trip, the training was terminated at the end of that trip; this was the case for four of the six student subjects.

Pilot Testing and Calibration

One MIT student, one non-MIT student, two employees from the Volpe National Transportation Systems Center with some level of rail experience, and one Amtrak engineer were used as pilot subjects to calibrate the fidelity of the simulator and our data acquisition process. After running one Amtrak engineer as a subject and updating the simulator based on his input, the rest of the experimental subjects were run while gathering data for future improvements. See the next chapter as well as "Appendix F: Future Considerations for the MIT/Volpe High-Speed Train Simulator" for a discussion of these suggestions.

Data acquisition and analysis

As the simulation progresses, data is automatically written to a log file. The time and location of any change in signal or failure scenario is automatically recorded, along with the train's location at the time of the change. Any time the engineer enters a control input (either via the traction lever or via the control stand), the time and nature of the input is recorded. In addition, the speed and location of the train is written to the log every 600 milliseconds. Thus, for each trip, the simulator provides a log file that can be used to analyze the dependent variables of interest—namely, authority/speed limit overruns (number and magnitude), reaction times and distances, station-stopping accuracy and schedule deviation.

Not all 48 data points that were collected as outlined above, for several reasons:

- Only three of the proposed six Amtrak engineers were able to drive the simulator in the time allotted to running experiments, due to scheduling difficulties. The other three subjects will be run as time permits; for more information, refer to the relevant report that will be published by the FRA upon completion of this phase of the research.
- An initial bug in the program precluded gathering data on the second of two preview displays used consecutively. Though the bug was fixed after one subject, we are unable to use the data for the variable-preview display from Subject E1 (the first rail engineer).
- After the first engineer's runs, the braking points were determined to be too aggressive[21] and were changed accordingly. Thus, we did not use the station-stopping data from Subject E1.
- Subject S3 (the third subject from the non-engineer group) uncovered a flaw in the robustness of the software. The circuit breakers, which are used for other experiments, toggle the motors off and on. They were disabled for the preview displays, but not for the no-preview displays. Subjects have no reason to hit the circuit breaker buttons, but Subject 3S displayed a propensity for hitting all the buttons. It seemed initially that the subject was only hitting the horn and the bell, though the bug was uncovered when the subject drove the train using the no-preview display (the last display used). The subject completed the first disturbance under this preview before uncovering the flaw. Thus, there is no data for one disturbance and three station stops. In the future, subjects should be explicitly instructed not to use these (and any other unnecessary) buttons and switches.

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[21] Subject 1E used the emergency brakes for three of the fourteen station stops. That subject's average absolute deviation was 13.6m, compared to 3.9m for the non-engineer subjects (after the braking points were changed). The subjects were told that -10m to +6m was the range of acceptable station-stopping deviation.

IV: Discussion of Results

There were several goals of this research: The primary goal was to examine whether the proposed information-aid improved safety and efficiency of train operation over an existing display, and if so, how much of the provided preview information is most useful. As discussed in the previous chapter, safety of train operation was measured by monitoring speed control, signal adherence, reaction time and reaction distance, while service level of train operation was measured by monitoring station-stopping accuracy and schedule deviation (though speed control could also be discussed as a measure of operational efficiency). Secondary goals included comparing the data gathered from MIT students with that gathered from Amtrak engineers, as well as compiling feedback from Amtrak engineers on the realism of the simulation to make recommendations for future simulator enhancements.

Speed Control

The term "speed control" here refers to the engineer's ability to maintain and stay below the permitted speed, once that speed has been reached. A violation of this requirement could take place during a clear signal, when the civil limit must be obeyed, or it could take place during a restricted signal, once the speed required by that limit has been achieved. Within the non-engineer group of subjects, there were ten such instances of speeding, while the engineer subject group produced four such instances.[22] The display numbers, 1 through 4, refer to the no-preview, 1.4-mile fixed preview, 3.4-mile fixed preview and variable preview displays respectively. There were more speed control violations with the no-preview display than with all of the preview displays combined, indicating that this task was more difficult for the test subjects using the no-preview display.

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[22] The automatic train protection (ATP) system, which governs the allowed speeds, was updated after the first engineer subject, as the system was not realistic. The simulation had been warning the engineer as soon as the limit was surpassed; in reality, the engineer is given a buffer zone of several mph over the limit, as outlined in the next paragraph. E1's speed control data were not used.

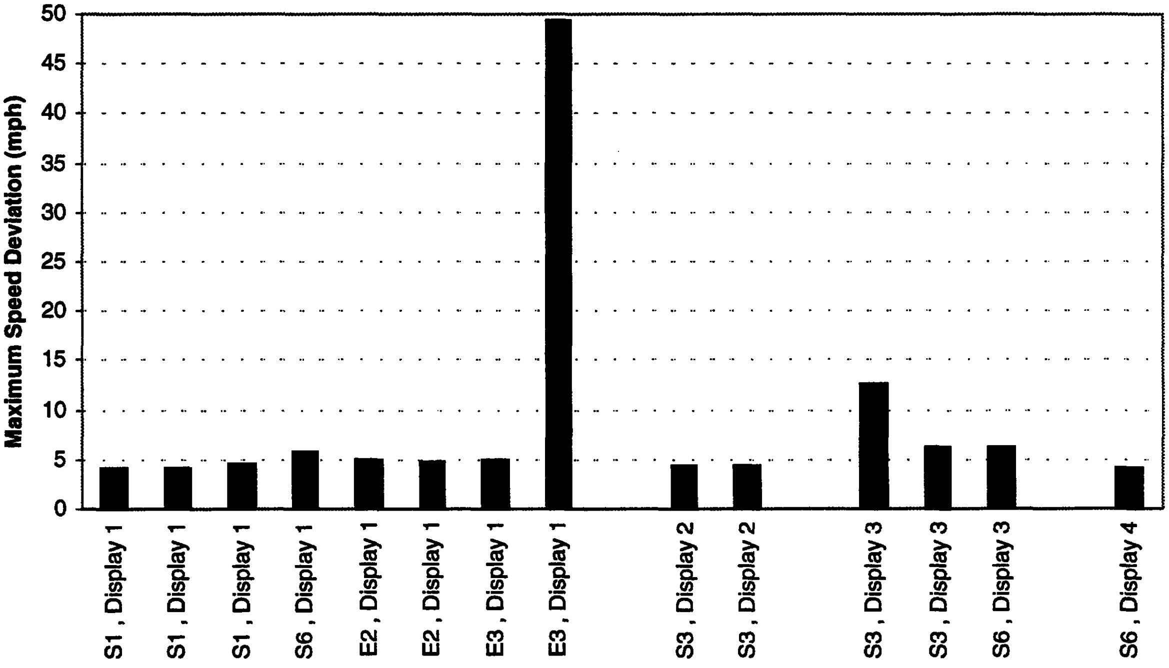

Figure 4.1: Cases of Speeding Under a Clear Signal Caught by the Train's ATP System (All Subjects: E = Engineer / S = Non-Engineer)

- Note that the minimum overspeed using three of the four displays was just over four mph. The automatic train protection (ATP) system in the MIT/Volpe simulator allows a "buffer" zone of four mph over the effective speed limit before any warning or punishment is given, which mimics Amtrak's system, though the size (i.e., number of mph) of the buffer zone in Amtrak's system can vary from train to train.

- In five of the ten instances of non-engineers speeding, Subjects 3S and 6S were approaching the point where the civil speed limit increases and were attempting to accelerate early. Of these five times that they were "caught" by the ATP system, the warning lasted from 0.1 to 5.1 seconds, and the maximum transgression reached as high as 12.7 mph. Subject 3S took a brief penalty application of the full-service brake after reaching 12.7 mph over the limit and being over the limit for five seconds. That application lasted less than a second, as the subject entered an area with a higher civil limit. One possible conclusion to draw from these two subjects' behavior is that they were induced to take the risk of "cutting the corner" on the speed limit increase by the preview display, which tells them that the speed limit is increasing. Using the simulation, the subjects could not build up enough knowledge of the system to know exactly how far away the point where the civil limit increases was, whereas (in real train operation) rail engineers know that information readily. The lack of resolution on the distance scale of the long-preview displays may have led to a higher likelihood of missing when "cutting the corner."

- Aside from the five instances of "cutting the corner" on the speed limit, and one other instance of a non-engineer speeding for just over one second under an "approach" (30 mph) signal with the variable preview display, all of the other eight instances of speeding occurred with the no-preview display. This indicates that routine speed control may be harder with the no-preview display than with the preview displays tested. Despite having had two full training runs, all of the engineers expressed how difficult it was to control the train without any previous knowledge of the train's "dynamics" (braking and acceleration characteristics). This difficulty was exacerbated when using the no-preview display which does not have a 25-second speed predictor, which indicates the location and speed of the train 25 seconds in the future based on current control inputs and upcoming track conditions, available on all of the preview displays.
- The most egregious speed violation was a subject from the engineer group who lost track of the train's location relative to the braking reference points, while using the no-preview display, and hit the 70 mph zone approaching South Station at 118 mph. He continued accelerating for several seconds before braking, and went to emergency braking after 53 seconds. The train hit the bunker at over 20 mph.

Signal Adherence

The term "signal adherence" refers here to the engineer's ability to control the train's speed in reaction to any unexpected signal differences or changes. While running the experiment, we learned from the engineers that they do not treat signal limits as absolute. That is, each signal limit tells the engineer something about the signal that succeeds it, and the engineer adjusts the train speed according to that information—an engineer might purposefully remain at 80 mph in territory governed by a signal that has dropped to "cab speed - low" (60 mph), knowing that the next signal is "approach medium" (45 mph), if the engineer knows he can control the train's speed according to the first possible upcoming stop signal. Due to this difference in control algorithm and the fact that operating a train at speeds greater than indicated by the signaling system is not seen as a safety hazard or as a poor reflection on the operator's driving abilities, we must take any conclusions based on "signal adherence" as a performance metric with a grain of salt. The subject groups performed similarly, with the most signal overruns in each group coming while subjects used the no-preview display. Performance with regard to red ("stop") signals, however, was nearly identical between the two subject groups and across the different displays.

	No-Preview	**1.4-mile Fixed Preview**	**3.4-mile Fixed Preview**	**Variable Preview**
Missed Signals	38	25	17	21
Average Length of Signal Overrun (miles)[23]	0.368	0.358	0.439	0.358
Average Initial Speed Deviation (mph)	44.8	57.7	70.1	70.2

Table 4.1: Signal Adherence Statistics for Non-Engineer Subject Group

	No-Preview	**1.4-mile Fixed Preview**	**3.4-mile Fixed Preview**	**Variable Preview**
Missed Signals	22	15	14	5
Average Length of Signal Overrun (miles)[23]	0.358	0.256	0.467	0.396
Average Initial Speed Deviation (mph)	32.4	48.5	59.1	68.1

Table 4.2: Signal Adherence Statistics for Engineer Subject Group

- For the non-engineer subjects, there were 101 missed non-clear signals. The no-preview display had the most signals missed despite having only seven critical disturbances in comparison to the other displays' eight disturbances (due to Subject 3S being terminated early, as described above, while using the no-preview display).
- For the engineers, there were 56 missed non-clear signals. The no-preview display also had

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[23] Does not include the eight overspeeds (three by engineers, five by non-engineers) in a crossover section, as these sections only last about 50 feet.

the most signals missed. The data above indicate similar performance from the two subject groups with respect to signal adherence, despite the above-noted difference in the engineers' expected speed control policy.

- The data in Tables 4.1 and 4.2 do not include the eight overspeeds (three by engineers, five by non-engineers) in a crossover section, as these sections only last about 50 feet. Four of these crossover overspeeds were with the no-preview display, one with the short fixed preview display, two with the long fixed preview display, and one with the variable preview display. Each of the rail engineer subjects expressed that the signals approaching the crossovers did not indicate that the crossover would be taken in the way they would in a real-world situation. The traffic preview available on each of the preview displays indicates which track will be taken, accounting for the lower number of overspeeds in these areas using the preview displays.

- The average length of overrun was shortest with the no-preview displays and the shorter of the fixed preview displays. I am not sure how to interpret these data. One possible explanation is that the subjects did not brake as aggressively while using the longer-preview displays, because they could see the distance in which they had to slow down, whereas with the no-preview display, they would not know when the next more-restrictive signal would come. Rail engineers know what each signal says about the possible signal levels for the next block and adjust their speed accordingly, often disobeying the signal level for the current block. For instance, if the signal for the current block is "approach medium," indicating a 45 mph limit for the current block and a probable "approach" (or 30 mph limit) for the next block, and the engineer knows the distance to the next block, the engineer may not slow the train down immediately, keeping some brake pressure in reserve and saving some trip time. However, the subjects were not familiar enough with the block and signal locations in the simulation to exhibit this behavior.

- The average initial speed deviation was lowest with the no-preview displays, indicating that the difference in total number of overspeeds consisted of deviations of smaller magnitude. Since the engineer must recognize and interpret each signal before reacting with the no-preview display, he or she might miss signals (to some degree) that would not be missed with the preview displays. These signals might be missed by only small speed deviations.

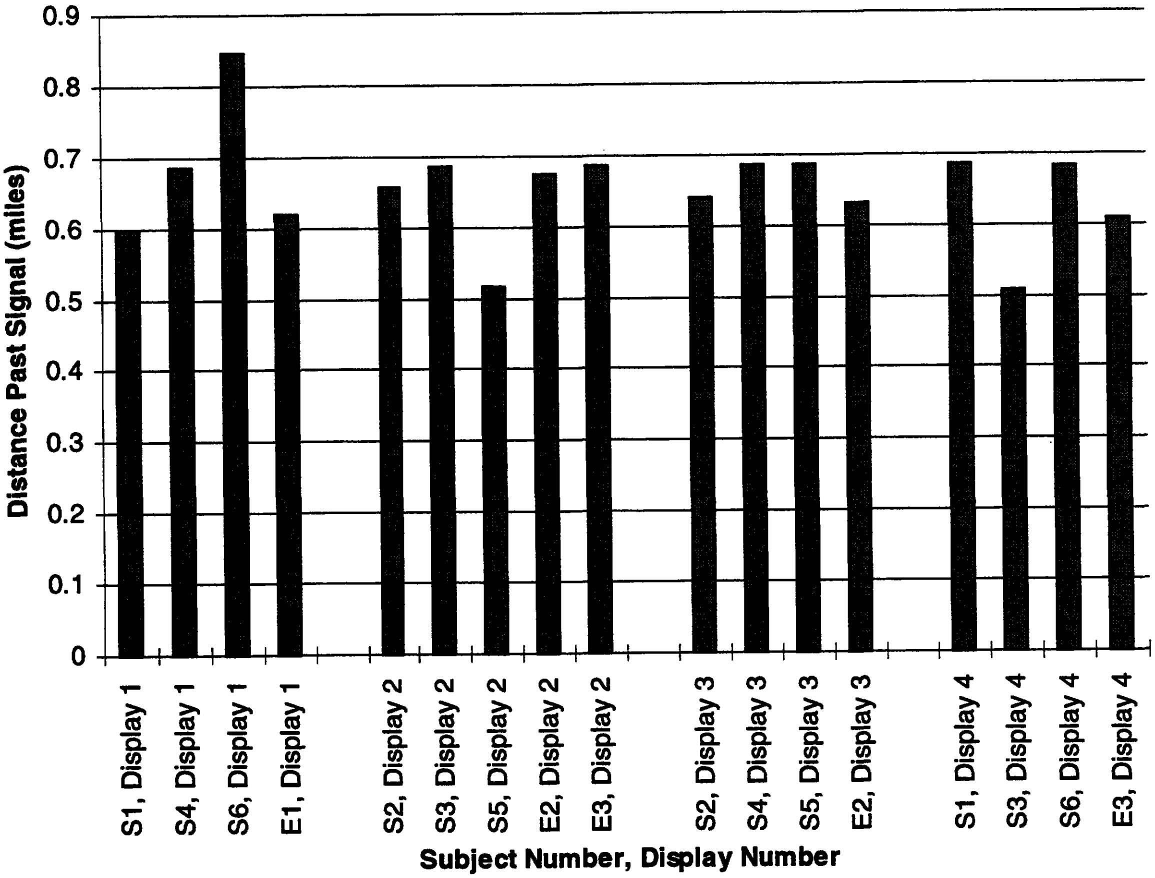

Figure 4.2: Stop Signal Overruns

One of the most dangerous situations in railroading is a train running past a red (or "stop") signal. As indicated in Figure 4.2, there were 17 such stop signal overruns among both subject groups and all displays during the course of these experiments. Each of these overruns corresponded to the situation where a signal "dropped in the face" of the engineer—that is, the signal turned red when it was already within the engineer's range of visibility. In no such situation was the engineer able to stop the train in time for the signal. As designed, the experiment had six such scenarios with each display (distributed among the twelve subjects). However, as previously explained, we were not able to collect all of these data points. Thus, the relative numbers of incidents are not as important to us as is the length of the overrun. Particularly, a shorter overrun indicates an improved ability to react to the sudden stimulus in the available time. The results are very similar, with two cases of markedly better reaction with the short and variable preview displays, respectively. However, the data indicate that in the case of a sudden critical scenario that is discernible out the window or in the cab (by way of the in-cab signaling), there is no significant difference between the preview and no-preview displays.

Reaction Time and Distance

As discussed previously, as train speeds increase, the rate at which engineers need to process information increases while their reaction time stays constant, leading to a decrease in the time available in which to react to stimuli such as signal changes. Both for the scenario in which the red signal was set from the beginning of the run (a "static" signal difference—Table 4.3), and for the scenario in which the signal was set when the train was within a few miles of the signal (a "dynamic" signal change—Table 4.4), we measured the time and distance between the first non-clear signal passed and initiation of braking. Negative numbers here indicate that braking was initiated before passing the signal—thus, the more negative the number, the greater the "cushion" between the act of braking and the more restrictive speed required by the non-clear signal. Reactions were improved with the preview displays, particularly the variable preview.

	No-Preview	1.4-mile Fixed Preview	3.4-mile Fixed Preview	Variable Preview
Reaction time (s)	1.7	-18.3	-5.7	-23.4
Reaction distance (mi)	0.069	-0.705	-0.255	-0.902

Table 4.3: Reactions Under Static Signal Difference

	No-Preview	1.4-mile Fixed Preview	3.4-mile Fixed Preview	Variable Preview
Reaction time (s)	1.87	1.32	.03	-2.51
Reaction distance (mi)	0.091	0.060	0.002	-0.115

Table 4.4: Reactions Under Dynamic Signal Change

The lower numbers associated with the preview displays indicate that the subjects were indeed afforded more time to react with these displays, though the data do not correlate directly with preview distance. There are several possible explanations for the lack of correlation, including:

- The nature of the signal changes was such that they had to be sent over the network, and the transmission time can vary somewhat from trial to trial.

- The signal changes associated with a red signal are sent in ascending order of block number, whether one is going to Boston or away from Boston. Thus a train traveling in the direction of ascending block numbers will be sent the signal change closest to the train first, while a train traveling in the direction of descending block numbers will be sent the signal change farthest from the train first. Thus, using the definition of reaction time based on the first signal change received, the second train is given more time to react.

Nevertheless, the data indicate that reaction time is better with the preview displays over the no-preview displays. In particular, for signals that have been altered before the train is within preview range, reaction time was reduced up to 25 seconds and almost one mile with the variable preview display. For signals that were changed when the train was relatively close to the signal (within preview range), reaction time was reduced up to four seconds and one-fifth of a mile with the variable preview display.

Schedule Deviation

Schedule adherence is one of the main metrics on which passenger rail operators are judged by their customers. As a result, it is also one of the important performance metrics for rail engineers. The data gathered, however, were inconclusive in this regard.

	No-Preview	1.4-mile Fixed Preview	3.4-mile Fixed Preview	Variable Preview	Scheduled (min)
S.Station—Sharon	6.53	5.89	6.85	6.48	7
Sharon—Foxboro		12.58	13.05		13
Foxboro—Attleboro	15.23		15.60	14.87	16
Loop	1.20	1.15	1.21	1.17	1.5
Attleboro—Foxboro		15.03	14.84		16
Foxboro—Sharon		13.01	12.99		13
Sharon—S. Station	7.47			7.42	8
Average absolute deviation (minutes)	0.44	0.57	0.44	0.65	

Table 4.5: Schedule Deviation by Display for Trips Without a Signal Change

As Table 4.5 indicates, there were very few schedule overruns in trips that did not contain signal changes. That is, each subject was able to get to the next station somewhat early almost every time. Though the subjects knew that they would be penalized for arriving at a station too early (see Appendix A), getting the most points off for arriving more than 60 seconds early, almost every trip without a signal change resulted in an early arrival (when a subject encountered a signal change, time was invariably lost, and the schedule could no longer be met, so we do not consider those situations). It was explained to each of the subjects that they should try to maintain the time differential between stations that was set on the schedule (e.g., "Always leave 13 minutes to get from Sharon to Foxboro, even if you are behind schedule."), but this consistently did not happen. The subjects may not have understood the directive, but a more likely explanation is either that the subjects forgot or that they simply referred to the schedule and tried to make up the time. The data above are not suitable for drawing conclusions on the effect that preview information may or may not have on schedule adherence. In future simulations, rather than the appropriate time differential, the new arrival time should be relayed to the subject at each station stop.

Station-Stopping Accuracy

The train engineer must be able to accurately stop at a particular point in the station to allow passengers to get out at the correct door (which is pre-determined by the conductor and relayed to the engineer). The inability to achieve such a stop smoothly and on the first attempt may result in excess fuel consumption, discomfort to the passengers (in the event of a "jerky" stop), or aggravation to the passengers (in the event that the pre-determined car is not adjacent to the platform, and the passengers have to relocate to exit the train), all of which reflect negatively on an engineer's performance. The subjects were told in the training material that deviations between -10m and +6m were acceptable, and that overshoots were penalized more than undershoots (as the engineer can always inch the train forward, but backing up is much more difficult and sometimes prohibited). The rail engineers seemed to have more trouble stopping accurately at the stations, and they expressed that this was due to a lack of knowledge of the "physical characteristics" of the system. The variation between the displays did not seem significant, and there was anecdotal evidence both in favor of and against the preview displays with regard to this task.

	No-Preview	1.4-mile Fixed Preview	3.4-mile Fixed Preview	Variable Preview
Non-Engineer Average Absolute Deviation (m)	3.5	4.8	3.2	3.6
Engineer Average Absolute Deviation (m)	9.5	6.5	4.9	4.1

Table 4.6: Station-Stopping Accuracy by Subject Group

- The data for engineers using the no-preview displays includes the 42.8-meter overshoot by the engineer who hit the bunker at South Station at 20 mph (described in the "Speed Control" section, above). Without that data point, the average absolute deviation for engineers using the no-preview display would be 4.9 m.
- If the above-noted data point is taken out, the 1.4-mile fixed preview has consistently higher deviations than the other two. One possible explanation for this would be that with the no-preview display, the engineer is focused on recognizing the braking reference points, while with the preview displays, the engineer relies more on the station marker on the instrument panel to aid with stopping—at top cruising speed of 150 mph, it will be too late to begin braking and still make the station stop. However, with the no-preview display no station-stops occurred in which the engineer had to resort to the emergency brakes, which casts doubt on this theory.
- Though one might expect that the preview displays would aid the engineer in judging the distance to the next station, and thereby ease the analysis regarding braking points, the same engineer who crashed into the bunker at South Station also resorted to the emergency brake to stop at two other stations, reaching the station-stopping points short by 30.9 m and 17.0 m with the short and long fixed preview displays, respectively. Taking away these data points, the average absolute deviations for the engineer subject group for those two displays become 1.7 m and 3.3 m respectively.

The closeness of the data presented in the tables above indicate that preview information has little or no effect on stopping accuracy. Some subjects reported having trouble stopping accurately with the preview displays. One subject, a rail engineer, "misjudged the braking distance [to the end of a station platform] by looking at the display and had to use the emergency brake." The display that subject was using was the 3.4-mile fixed preview display, which offers very poor resolution for accurate stopping from low speeds. Several other subjects, both students and engineers, reported trouble using the fixed-preview displays for accurate station-stopping, supporting the assertion that these displays are not well-suited for aiding accurate stops. Nevertheless, subjects continued to use the preview displays to help decide when to start braking from higher speeds.

These anecdotes suggest that the subjects learned to rely on the preview displays for general help with regard to stopping the train, and that further effort should be put into developing similar aids for accurate stopping. One possible solution is to increase the resolution of the preview displays at lower speeds, either in discrete steps at predefined intervals or continuously, to allow the engineer to better judge from the display itself the distance to the appropriate stopping point. However, several of the subjects expressed that the one thing they did not like about the variable-preview display was the need for constant recalculation of the scale of relevant points on the preview display screen. This does not bode well for a screen that would change the resolution right when the display is needed, as might be the case in station-stopping. Further study needs to be done on the best way to accomplish such aiding, particularly with respect to this discrete or continuous re-scaling.

A confounding factor that also needs to be examined further is that engineers rely heavily on knowledge of the train's deceleration characteristics and out-the-window (visual) reference points when stopping at a station—without the experience to build up a similar knowledge-base, the engineers may be forced to rely on whatever new tools are provided to them. The question remains whether engineers would find such tools useful on terrain with which they are familiar.

Comparison of Performance and Behavior of Engineer vs. Non-Engineer Subjects

The two subject groups, engineers and non-engineers, performed similarly in this experiment:

- The data in Tables 4.1 and 4.2 indicate similar performance between the two subject groups with regard to signal adherence.

- The data in Figure 4.1 indicate similar performance between the two subject groups with regard to speed control, though two of the non-engineer subjects displayed a propensity for trying to accelerate to an upcoming increased speed limit before approaching the speed limit. This type of behavior may not be acceptable for locomotive engineers on an ongoing basis.

- The data in Figure 4.2 indicate similar performance between the two subject groups with regard to "stop" signal adherence when no warning is given.

There were two exceptions to the similarity of the subject groups' performance:

- The non-engineer group performed consistently better than the engineer group with regard to station-stopping accuracy. The engineers complained that their lack of knowledge of the train's dynamics and the track features led to the poor station-stopping results.
- Tables 4.7 and 4.8 indicate that the non-engineer subjects had faster reactions under all of the displays except for the no-preview displays. (Negative numbers here indicate that braking was initiated before passing the signal—the more negative the number, the greater the "cushion" between the act of braking and the onset of the more restrictive speed.)

Table 4.7. Reaction Times Under Static Signal Difference (by subject group)

	No Preview	1.4-mile Preview	3.4-mile Preview	Variable Preview
Engineers	1.4 s	-15.7 s	-4.5 s	-19.1 s
Non-engineers	1.8 s	-20.0 s	-6.2 s	-27.7 s

Table 4.8. Reaction Times Under Dynamic Signal Change (by subject group)

	No Preview	1.4-mile Preview	3.4-mile Preview	Variable Preview
Engineers	1.6 s	1.5 s	1.2 s	-0.3 s
Non-engineers	1.9 s	1.2 s	-0.7 s	-3.4 s

The differences between the two groups with regard to station-stopping seemed to be a direct result of the engineers' usual reliance on their knowledge of the "physical characteristics" of the train and track to stop accurately at stations, coupled with their lack of such knowledge while using the simulator. This problem could be solved by implementing a system whose dynamics and track characteristics are more similar to those the engineer might have experienced before.

The difference in reaction times indicates that the non-engineer subjects had quicker reactions using the preview displays than the engineer subjects did, though the engineers had slightly faster reactions than the non-engineer subjects using the no-preview display. This would indicate that the engineer subjects would not have been as safe when using the preview displays as the non-engineer subjects, though the signal adherence data does not seem to bear this out. The difference in the engineers' reaction times between the no-preview and preview displays makes sense in light of the engineers' expressed need to focus attention out the window, thus keeping their attention away from the tool that would allow them to react sooner. The non-engineers, who are not inhibited from focusing their attention in the cab, were able to more quickly detect stimuli that are found only in the cab (and not out the window). More research is needed to determine whether the engineers' attention allocation scheme would hamper efforts to deliver more information via an in-cab display.

V: Conclusions and Recommendations[24]

Summary

The data gathered in these experiments suggest that preview information is a useful tool in train control, and that the engineer should generally be able to preview at least the minimum stopping distance of the train. Furthermore, the data gathered from the two subject groups (rail engineers and non-engineers) correlated well, indicating similar levels of performance; further research should be done to see if the engineers' lack of knowledge of the track and train characteristics influenced their behavior.

More specific results include:

- Routine speed control under a static signal was improved with the preview displays, though again, it is unclear whether this difference would exist for the rail engineers if they were more familiar with the territory and train's dynamics.
- The number of signal overruns was decreased with the preview information.
- Reaction time was markedly improved with the preview information, particularly with the variable preview display.
- Preview information did not seem to have an effect on station-stopping accuracy, though the 1.4-mile (shorter) fixed preview display resulted in station-stops that were more deviant than with the other displays. There was anecdotal evidence in favor of each of the types of display with respect to station-stopping. All of the preview displays received high marks for providing good information regarding stopping distance from higher speeds, while the variable preview display also received praise for increasing the resolution at lower speeds, thereby allowing more accurate stops.
- Among the preview displays, performance with respect to signal overruns was poorest with the 1.4-mile fixed preview display.

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[24] Recommendations for future simulator enhancements are discussed in "Appendix F: Future Considerations for the MIT/Volpe High-Speed Train Simulator." This Appendix also includes some interesting anecdotes and observations regarding the Amtrak engineers' interaction with the simulator.

- Subjects using the 1.4-mile fixed preview display during dynamic signal changes did worse than with other preview displays, while subjects using the 3.4-mile fixed preview during static signal differences did worse than with other preview displays. Subjects using the variable preview performed best in both of these scenarios.

Recommendations

Anecdotal evidence seems to support the data described above that long preview or preview that scales with speed (offering greater resolution at lower speeds) is preferable. As one subject put it:

> The 3.5-mile preview display made control easiest. The reason I felt variable preview was a little less effective is because you (the operator) [sic] had to sort of scale distances as a part of the interpretation—it took some getting used to. The 1.5-mile display was my least favorite of the preview displays because you could not see the entire predicted braking curves at high speeds.

When asked what preview distance would make the job easiest, most of the subjects responded "as much as possible" or referred to either the 3.4-mile fixed preview or the variable preview, while one engineer responded "5 to 10 miles." Another engineer responded, "No preview is needed if you know the physical characteristics [of the train and track]," though a much higher processing burden is then placed on the engineer, particularly in critical situations. In general, preview distance should be at least the minimum stopping distance plus some buffer distance to account for reaction time.

The Amtrak engineers who participated as subjects generally reacted favorably to the preview displays, particularly since they "helped learn the territory." It is unknown whether the engineers would have found the preview displays as useful if they already knew the territory and the train's dynamics, and further research is needed in this area.

In designing such information aids, particular attention needs to be paid to how the engineer allocates his or her attention—though the engineers who drove the simulator seemed to like the preview displays and performed well with them, at least two of the engineers stressed their need to focus attention out the window. One engineer complained about the amount of "electronic harassment" in modern locomotive cabs precluding engineers from focusing their attention out the window,[25] though that same engineer did acknowledge that the preview displays aided navigation in unfamiliar territory and that it was useful to see the rate of deceleration relative to distance.

With regard to accuracy of station-stopping, there was evidence that the preview displays had a negative effect, due to the lack of resolution at lower speeds. For a preview display to be an effective tool at wide ranges of speed, not only should enough preview distance be provided at higher speeds, but enough resolution (of distance) should be given at lower speeds to allow for accurate stopping. Further work in this area is needed, particularly with regard to how this change of resolution should take place (e.g., continuously or discretely).[26]

The data indicate that the non-engineer and engineer subject groups exhibited similar behavior towards signal adherence and speed control, though the reaction times to stimuli on the dashboard (i.e., signal changes that could be seen only on the preview display, and not out the window) were longer for the engineers than for the non-engineers. This indicates that the engineers were inhibited from focusing their attention in the cab, keeping them from making full use of the proposed decision aids. This is supported by the engineers' assertions that they need to focus their attention out the window. The non-engineers' performance indicates that removal of such inhibition (perhaps by increased training) would improve reaction times. Future work should focus on how locomotive engineers allocate their attention, and on how to effectively incorporate decision aids and training for those aids into that attention allocation scheme.

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[25] That subject expressed that the engineer's attention is not necessarily needed to be able to brake in time for a potential emergency, but rather to be able to blow the horn in time in such a case, or to accurately control the train when approaching a bunker or a platform. In fact, this subject related that many engineers "cut out" (turn off) the in-cab signaling and ATP when in low-speed territory to remove the "distraction" of the warnings and focus their attention on very fine control of the train's speed. However, the danger is that they forget to cut it back in.

[26] One possible experiment to investigate this question is to allow the engineer to control the preview distance and record what is chosen as a function of speed.

Appendix A: Training Tutorial[27]

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[27] This Appendix borrows heavily from Appendix A of Lanzilotta [1996]. The tutorial for the rail engineers did not include certain sections, particularly those discussing the payment system and those that discuss the block signaling system and the payment system.

Experiment—General

This is an experiment to shed light on the relationship between the type of information an engineer receives and his or her ability to react to critical scenarios during high-speed rail operation. As trains travel faster, engineers have less time to react to events that occur both outside the train and inside the cab. One suggestion to counteract the diminishing amount of time available for reaction is to provide the engineer with a "preview" of the status of the track a certain distance ahead of the train, allowing more time to react to changes in that status. To explore this idea, test subjects like yourself are asked to operate a simulated high-speed train in a "virtual reality" environment. Your actions and reactions are measured, and later analyzed.

Participation in the experiment consists of two phases. The first phase is a period of training, consisting of a three-hour instruction session and a three-hour practice session. Prior to the instruction session, you are asked to review this document, which is a tutorial on the operation of the simulated train. At the start of the instruction session, you will be questioned on the tutorial, to gauge your understanding of this material (25 multiple-choice questions). The experimenter will go over any wrong answers with you to ensure your understanding of the operation of the simulator. You will then be directed by the instructor through a set of training trips (approximately two hours), to familiarize you with normal operation of the train, the track you will be traveling on during the experiment, and the various dashboard displays that will provide you with information. You will also be told about some abnormal events that may occur and the proper response to these situations. You will be given ample opportunity to have any questions answered concerning the operation of the train.

The second half of the training is a combination practice and test session. This session, like a regular experiment session, is four hours, consisting of two round trips between the two system end-stations. These trips will be under experiment-like conditions. Your performance will be evaluated with regard to speed compliance, signal compliance, and station-stopping accuracy. If you pass this test, you will be considered ready ("certified") to perform the experiment trials. Whether or not you are accepted to continue with the trials, you are eligible for payment for the training phase upon completion of the practice and test sessions.

The second phase of your participation in the experiment consists of a set of experimental trials, which take place during one four-hour session. The session is divided into four trips of equal length, corresponding to four trips an engineer on a short stretch of track might make in a given shift. During each trip, you will operate the simulated train as if it were part of an actual rail system. Once you begin, you will be expected to remain at the simulator control in the "cab" of the train until the trip is complete. There will be brief break periods between each trip. The training and experimental trials will take place on separate days. You will be eligible for payment for the experimental trials upon completion of the entire shift.

Payment for the experiment, through the MIT voucher payroll system, is at $10 per hour. Thus, the sub-total for the training phase is $60, while the sub-total for the experiment phase is $40 plus bonuses, resulting in a total payment of $100 plus bonuses. (Payment for the experiment phase is subject to performance bonuses, as well as penalties that result from illegal behavior—please refer to the section titled, "System Operation—Operator Performance Requirements," for more details.) Subjects are paid for each phase completed, regardless of performance; however, subjects that do not pass the training phase will not continue with the experimental phase. Subjects can elect to be paid separately for the training and experimental phases (resulting in two checks), or payment for the two phases can be lumped together into one check.

This tutorial is organized to teach, in a logical order, the fundamentals of rail system. Important terms and concepts are highlighted in bold-faced text.

System Operation—General

The rail system runs between South Station (Boston) and Attleboro, MA (just north of Providence, RI), a stretch of track used regularly by the MBTA commuter service (see "Brake-Point Specification Worksheet," attached, for a schematic overview of the rail system—these maps will be on the wall and desk of the cab as well). The two end-stations are connected by a set of parallel tracks which run from Attleboro north to Sharon, and then separate somewhat before converging outside South Station. Round-trips start from South Station and continue to Attleboro; from there, the trains loop around before beginning the return trip to South Station.

The simulation is operated as a high-speed commuter service between South Station and Attleboro, with stops at two intermediary points (Sharon and Foxboro). Your shift will consist of two round-trips. You will begin at South Station and travel to Attleboro. You will discharge your passengers, close the doors, loop around and wait at Attleboro for boarding passengers. While waiting, your dashboard display will be changed. You will then close the doors and return to South Station. During each trip between South Station and Attleboro (or vice versa), you are expected to stop at each of the two intermediary stations to discharge and board passengers.

Operation of the system is coordinated through a **central traffic controller (CTC)**. This person is located in a fixed position in the system, and has access to the status of all trains operating in the system. The CTC coordinates the operation of several trains that must share the track. To do this, the CTC controls the switches in the system, and sets signal levels. In addition, the CTC can communicate directly with individual train operators—by way of two-way walkie-talkies. (See sections below titled, "System Operations—Communications" and "System Operation—Role of the CTC" for more information.)

System Operation—Block Signal System

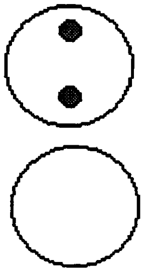
Rail systems traditionally use a system known as "block signaling" to control trains in the rail system. Using this system, the track is divided into fixed-length segments, known as "blocks." While the length of each block does not change, different blocks are not necessarily of equal length. Typically, shorter block lengths are used in the vicinity of stations, while longer block lengths are used in regions further away from stations; this is done to achieve tighter control over trains' speeds in area where there is more likely to be many trains. Block lengths are generally about a mile or less. In the rail system used in the simulation, the blocks near South Station can be as short as 100 yards or so, while the blocks closer to Attleboro can be up to 1.5 miles long.

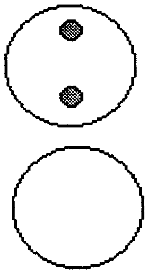
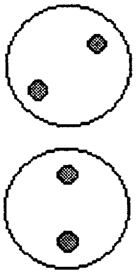
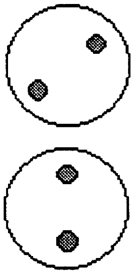
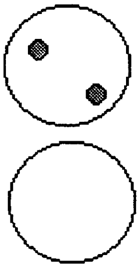
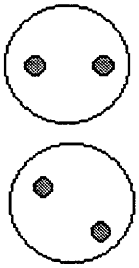
Every stretch of track has a **civil speed limit** which never changes. These limits are not posted and are either memorized or written down by the operator (see the "Brake-Point Specification Worksheet" and attached map, found at the end of this tutorial and also in the simulator cab). As you enter each block, you will see a signal light above the track. The signal light displays a coded signal, which indicates the maximum speed permitted throughout the block. This **block signal** acts as a dynamic speed limit, modifying the civil speed limit that is in effect in that block. The lower of the block signal and the civil speed limit is the limit that must be observed. It is the responsibility of the train operator to identify the signal as the block boundary is approached, set the train speed accordingly (remembering the civil speed limit), and maintain that speed throughout the block.

For example, in a stretch of track near a station, the civil speed limit may be 30 mph—a "clear" block signal (described below) at the beginning of a block would mean that a train entering that block has authority to travel at speeds up to 30 mph, while an "approach limited" signal, which limits the speed to 45 mph, would have no effect, and the train would still have the authority to travel only at up to 30 mph. However, in a stretch of track between stations, the civil speed limit is 150 mph—a "clear" block signal at the beginning of this block allows the train entering that block to travel at speeds up to 150 mph, while an "approach medium" signal would limit the train's speed to 45 mph.

The fundamental concept of block signaling is that no more than one train can occupy a block at any given time. A red ("stop") signal is used to indicate that a block is currently occupied by another train, and a second (approaching) train is not permitted to enter that block. The signals for the blocks that precede the occupied block ensure that the approaching train can be slowed in time to stop before entering the occupied block.

In the simulation system, a nine-signal system is used. This means that there are nine codes (plus "stop") used in the system, as shown in Table A.1. (Note: Amtrak considers the three levels of "clear" and two levels of "cab speed" as each being distinct.)

Signal Aspect	Signal Label	Signal Meaning
	CLEAR	Stay below civil limit and the speed indicated by the in-cab system (which will be either 150, 125 or 100 mph)

 (flashing)	CAB SPEED	Stay below civil limit and the speed indicated by the in-cab system (which will be either 60 or 80 mph)
 (bottom signal flashing)	APPROACH LIMITED	Stay below civil limit and 45 mph
	APPROACH MEDIUM	Stay below civil limit and 45 mph
	APPROACH	Stay below civil limit and 30 mph
	RESTRICT	Stay below civil limit and 20 mph

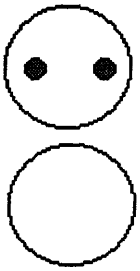
	STOP	No authority to move

Table A.1: Block signal aspects

The signals preceding a "stop" signal (or any more restrictive signal) are set to give the train operator enough time to bring the train down to the specified speed. The train is allowed to exceed the speed indicated by the in-cab signal system, but only if full-service braking is being applied. Any time a more restrictive signal is encountered, an audible alarm goes off until full-service braking is applied. Figure A.1 shows the typical speed profile and signal settings for a train approaching a "stop" signal from 150 mph. Note that the train enters each successively restrictive speed zone at speeds greater than the speed indicated by the signals—this is allowed only because braking is assumed to be applied in the figure; remember that the signals are set to allow the train operator enough time to reach the final indicated speed by the indicated location. A digital cab signal that flashes between a number and zero indicates that you should not go faster than that speed, and be prepared to stop.

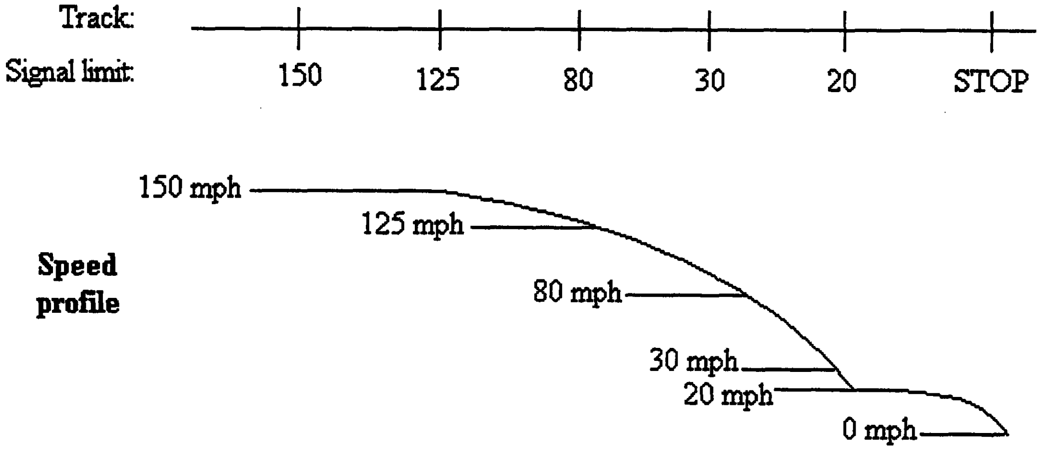


Figure A.1: Typical Signal Settings and Speed Profile for a Train Approaching a "STOP" Signal From 150 MPH Territory

Located on the side of the track throughout the system are position markers known as mileposts. The use of these by train operators is discussed in detail in the next section. It is important to note the difference between block signals and mile posts. At the entrance to each block, there is a **signal board** which identifies the block number and displays the current signal level for that block. Because block boundaries (generally) occur at irregular intervals, as opposed to the regularly spaced mileposts, there is no correspondence between the mileposts and the block boundaries. Operators must take care to differentiate between the two.

Train Operation—User Interface

The user interface for the train simulation consists of two displays, a computer keyboard, and the combined (traction/brake) control lever. The "out-the-window" view is projected onto a 10-foot diagonal screen in front of the cab, while the instrument panel is sunk into the cab desk top.

Genesis Display

During your trips, you will use one of two different instrument panels. The first is based on Amtrak's Genesis II locomotives, shown in Figure 3.2. The signals to the left are in-cab replicas of the wayside[28] block signals, though the in-cab versions also include digital readouts of the block signal limit and the civil limit. The more restrictive signal will be highlighted to aid in determining the effective speed limit—again, as the operator of the train, you must obey the more restrictive limit. There is no in-cab signal for "stop"—if none of the signals is illuminated, the "stop" signal is assumed. In the middle of the screen (from top to bottom) are the speedometer, traction level (braking and thrust in one readout), and the brake gauges. To the right of the brake gauges are various warning and status lights.

Preview Display

The second display you will use (the "preview display") is shown in Figure 3.3. It has many of the same elements as the first (note the traction level display and the brake gauges to the right of the display), as well as warning and status lights at the top that are similar. In addition, this

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[28] **Wayside** refers to all objects in the environment outside the train (i.e., anything that does not move). This includes items such as the ground, the track, the external signal lights, the surrounding trees and buildings, and so on.

second instrument panel has two preview displays—the upper (larger) display shows the upcoming speed limits (as well as curves indicating the stopping distance using full-service and emergency braking, and where the train will be in 25 seconds given the current inputs), while the lower (smaller) displays shows the upcoming track, authorities and traffic. This second display does not include the in-cab signals or any digital reading of either the block signal or civil speed limits—instead, the effective speed limit is displayed graphically as a red line on the distance-speed preview display in the middle of the screen. The **effective speed limit** is the more restrictive of the block signal and civil speed limits.

The projected view is a representation of what the operator sees out the windscreen of the cab. The environment in which you will operate is a night view with various trees, buildings and houses by the wayside.

The combination control lever is a joystick-like lever to the right of the keyboard. This lever is used to control both the thrust and braking commands, with the forward (up) direction for thrust and the backward (down) direction for braking. The center position (coast) is notched for reference. The center position ("neutral") ranges from slight braking to slight acceleration—care must be given to monitoring the amount of thrust or braking applied.

Two control stands are used for control inputs, the operation of which is described in the following sections.

On the cab desk is a two-way radio, which is tuned to same frequency as the CTC for remote communication. You must report station arrivals and departures to the CTC, and any schedule changes will be reported to you over the radio.

Train Operation—Speed and Position Control

The most important task required of a train operator is the control of train speed. Based on the position of the train, the operator determines the civil speed limit (which is either memorized or written down). Then, based on the current block signal, the operator determines the effective speed limit. The operator then uses the traction motor and braking systems to adjust the speed of the train accordingly.

The train operator gets information about train speed through the speedometer, which is located on the instrument panel in the locomotive cab. In the Genesis-style display, the speedometer is linear and horizontal; in the preview displays, the speed is indicated as a bar (representing the train) that rises vertically along the current-position line. On both displays, the maximum displayed speed is 180 mph; the major increments of the display are 20 mph, while the minor increments (present on the preview-display only) are 5 mph. On the Genesis-style display, the cruise speed (if any) is indicated in the lower right-hand corner. On the preview displays, the green line emanating from the representation of the train indicates the speed and location of the train in 25 seconds, given the current inputs.

Another important task of the train operator is monitoring the position of the train in the rail system. Generally this is done by monitoring the out-the-window view; when using the preview displays, this task is aided by the availability of both of the preview displays which provide the mileposts in addition to the speed limits and future authorities. Along the wayside, distance is marked through the use of mileposts. Typically, at one mile intervals, a post is placed on the wayside with numbers indicating the mile marker. Train operators use the difference between posts to measure distances along the road.

When approaching a stopping point, such as a station, the train operator uses out-the-window cues to identify points at which the brakes should be applied to stop at a particular position. Because of the high mass of the train, accurately braking the train requires relatively long lead times. It is common for train operators in real systems to use stationary objects on the wayside as braking point markers. Learning the proper braking points represents a significant part of the training process for train operators.

To assist in learning and remembering the appropriate braking points, significant landmarks placed in the wayside environment as well as the block signals and mileposts help locate the braking points. During the training phase, you will be provided with a "Brake-Point Specification Worksheet," along with a schematic diagram of the track, to help identify the speed restricted areas, as well as the braking points for these areas. The chart also identifies the landmarks which are placed near each braking point. This chart and the associated maps can be found in the simulator cab, on the walls and desk.

There are three civil speed limits throughout the system: The speed limit in and around the two end-stations (South Station and Attleboro) is 30 mph, as is the speed in any crossover between two parallel tracks—you will not normally be traveling on these crossovers, but in the event of a maintenance crew in the right of way or an expected opposing train, you may be required to change to a parallel track. Just outside South Station, the speed limit is 70 mph, indicating that there is heavy traffic in the area. The rest of the track, including the track that runs through the stations, is rated at 150 mph. Though you can travel through a station at 150 mph, you must stop at each of the stations in this simulation.

The skill of stopping the train at the station is a critical component of train operation in passenger rail systems. Figure A.2 will assist you in learning this skill. In reality, the optimal stopping point is determined on a station-by-station and case-by-case basis (i.e., the proper stopping point may change from trip to trip). In the simulation system, however, the ideal stopping point in the station is defined as the point at which the front of the train is at the end of the platform (i.e., the end of the platform to the right of the train is at the edge of the out-the-window view). Each platform is about 200 feet long, and there is a post towards the end of the platform that will be useful in determining when to brake.

Figure A.2 provides a summary of the braking distances from low speed, using full-service braking. From the information provided in the figure, the following strategy for accurate station stopping can be determined:

1. Enter the platform area at about 17 mph.
2. Apply full-service braking as the train reaches the platform.
3. When the train slows to about 8 mph, ease off the brakes to coast.
4. When the end of the platform is about 15 feet away (when you pass the post on your right), reapply full-service braking.

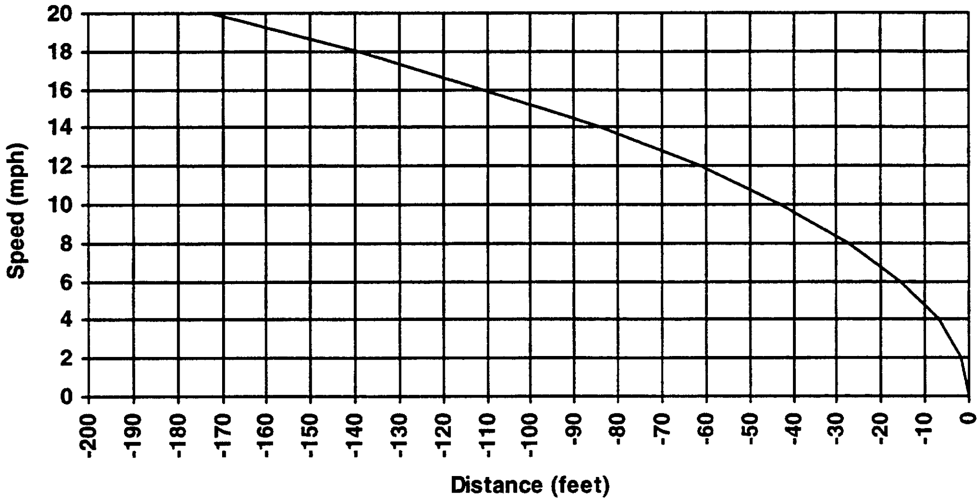


Figure A.2: Braking Distances at Low Speed (Using Full-Service Braking)

In addition, Figure A.2 shows that entrance to the platform area at a speed in excess of 20 mph will result in an overshoot, and may result in a missed station stop.

Train Operation—Control Modes

There are two basic control modes available with the high-speed rail simulation train: Manual mode and cruise control. In manual mode, you will be responsible for all aspects of train control. The combination control lever provides all thrust and brake commands required to achieve speed and position control of the train.

In cruise control mode, the automatic control system applies the appropriate level of thrust force to maintain a constant speed setting. When using cruise control, you will be responsible for determining the proper speed for the conditions, and then enabling the cruise control system (by depressing the "Cruise Control" switch, on the left control stand) at that speed. In addition, you will be responsible for regaining manual control if necessary (e.g., due to an upcoming restricted speed limit). When operating in cruise control mode, the "Cruise" status light will be illuminated. The Genesis-style display provides a digital readout of the set speed in the lower right-hand corner.

When the cruise control is first selected, the control system will adjust itself to determine the proper level of thrust force required to maintain the selected speed. As a result, there is a small amount of "hunting" around the set speed at first. The system then settles down to the set speed, and small fluctuations in the motor current indicate that the control system is operating.

From cruise control mode, the you can select manual mode in two ways. Depressing the "Cruise Control" switch while cruise control is activated will deactivate the cruise control and return manual control of the train to you. Actuating the brake (by pulling back on the traction lever past the neutral point) will also deactivate the cruise control; moving the control lever in the thrust region (i.e., forward of the neutral position) while cruise control is activated has no effect on train operation.

For safety reasons, brake application will always disengage the cruise control system. As a result, it is impossible to engage the cruise control system when the brakes are in use. If the operator attempts to engage the cruise control system while the brakes are applied, the system will not respond to this command, and the train will remain under manual control.

Train Operation—Traction System

In our simulation, high-speed trains are propelled by electric motors, called traction motors. Power for the traction motors is fed from a high-voltage line, usually on overhead wires or track-side rails. The power is then passed through a motor controller, which governs the amount of power supplied to the traction motors based on the control command of either the train operator or the automatic control system.

In the manual operating mode, you are in direct control of the traction power, and consequently, the acceleration of the train. When the control lever is in the center position, no tractive power is provided, and the train coasts. Moving the lever back increases the braking force. In the automatic (cruise control) mode, the level of tractive power is determined automatically by the control system, and a control command is provided to the traction motor controller. In either control mode, the level of tractive effort (positive for thrust, negative for braking) is displayed on the horizontal display on the instrument panel.

Train Operation—Brake System

Train brakes utilize air pressure, which is stored in tanks on the locomotive. Under non-braking circumstances, the pressure in the tanks (and pipes connecting these tanks to the brake cylinders themselves) prevent the brakes from engaging. When the brakes are applied, pressure is released from the pipes, causing pressure to be diverted to the brake cylinders and the brake shoes to contact the rotating surfaces of the wheels, thereby slowing the train. An important variable to be monitored by the train operator is the brake pipe pressure, to make sure that there is enough pressure available to stop the train.

The braking system has two modes of operation—service braking and emergency braking. During normal operation, the train operator uses service braking to apply various levels of braking force to the train. In this mode, the level of service brake application is controlled by the combination control lever. The level of braking force can be varied continuously throughout the available range. Application of the maximum available braking force is known as full-service braking.

In the emergency braking mode, all of the pressure in the brake pipes is released, resulting in the maximum available possible brake force. In general, this is not a desirable event, as the forces generated result in severe deceleration, which can damage equipment and can cause discomfort, or even injuries, to passengers. The train operator can command an application of the emergency brake via the "emergency brake" button on the left control stand. Also, in certain operational modes, the emergency brake will be applied as a result of dangerous condition or improper control actions Such application of the emergency brake is known as a penalty application.

During application of the emergency brakes, the emergency brake indicator will be lit (red). Once the emergency brakes have been applied, they cannot be released until the train comes to a complete stop. When the train is stopped, the control lever must be pulled back to a position which results in application of the service brake, and the emergency brake "reset" switch on the left control stand can be toggled. At that point, the emergency brake indicator light will be extinguished, indication that the emergency brake has been released and the train is ready to continue with normal operation.

The pressures in the various parts of the brake system are indicated by the horizontal gauges on the instrument panel. The gauges are calibrated in units of pounds per square inch (psi), with a range from 0 to 140 psi. In order from top to bottom on the screen, these are:

1. The **equalizing reservoir** should always remain between 50 and 90 psi—values outside this range indicate an imbalance between the brake pipe and the brake cylinder.

2. During normal (non-braking) operation, the **brake pipe pressure** should be between 110 and 130 psi, indicating that there is enough pressure to stop the train. During minimum to full-service braking, this pressure to drop to between 50 and 70 psi, indicating that the proper amount of pressure has been transferred to the brake cylinder to stop the train. During emergency braking, the brake pipe pressure should fall to between 25 and 40 psi.

3. The "**reduction**" indicates the level of braking. During normal (non-braking) operation, the reduction is zero. During minimum to full-service and emergency braking, the reduction rises from 5 to 25.

4. During normal (non-braking) pressure, the **brake cylinder** will have a nominal (non-zero) pressure of a few psi. The pressure should rise to between 60 and 90 psi for full-service braking and between 90 and 110 psi for emergency braking. The pressure in the brake cylinder is the pressure that is actually going to stopping the train—too little pressure means the train won't stop, while too much pressure could cause damage and/or injuries.

5. The fifth gauge is an "end-of-train" monitor, and is only functional on freight trains.

6. The **main reservoir**, which is read digitally at the bottom of the other brake displays, should always remain between 120 and 130 psi—values outside this range indicate that there is not enough pressure available to stop the train.

Any brake display value above 140 psi is extremely dangerous and could cause serious damage. Any situation in which abnormal brake display readings persist indicate that the CTC should be notified and the train brought immediately to a stop to investigate the cause.

Train Operation—Alerter System

The alerter system is a safety system on the train, which reduces the risk of accidents which are due to operator incapacitation or inattention. The principle behind the system is the requirement for periodic input from the train operator, to determine if s/he is still functional at the controls. If the operator does not respond in a reasonable amount of time, the system assumes that s/he is incapacitated and applies the emergency brakes to stop the train.

The alerter system, as implemented in the high-speed rail simulation, is similar to those used internationally in actual rail systems. If you do not depress the alerter response button (on the left control stand) or give some sort of control input (such as a traction control lever movement) within a certain period of time from the last depression of the alerter response button or control input, the system issues a warning reminding you to do so. The warning consists of a flashing yellow indicator light on the instrument panel and an audible chime. If you do not respond within ten seconds of the onset of this warning, the system assumes that you are incapacitated and applies the emergency brakes. In this scenario, both the alerter warning light and emergency brake lights will be illuminated until the train comes to a complete stop and the emergency brake is reset (by toggling the "Emergency Brake Reset" button). The time period between alerter warnings varies from 50 seconds at lower speeds to 10 seconds at the top system speed of 150 mph.

Train Operation—ATP System

The automatic train protection system (ATP) is a safety system designed to reduce the risk of accidents due to overspeed conditions. An overspeed condition is defined as operation of the train at speeds in excess of either the civil speed limit <u>or</u> the block signal speed limit.

The ATP system continuously monitors the speed and position of the train. It also identifies the state of the block signal when a block is entered by the train. Based on the position of the train and the block signal state, the maximum allowable speed is determined (this system gives a "buffer" zone of four mph above the effective limit). If the train exceeds that speed, an audible alarm is sounded and a warning light on the dashboard display is illuminated. Any application of the brakes will turn off the audible alarm, though the overspeed light on the instrument panel will remain illuminated until the train's speed is below the effective speed limit. If the train exceeds the effective speed limit by more than 3 mph for more than five seconds, a penalty application of the full-service brakes is applied—control of the train is not returned to you until the train's speed is below the effective speed limit. If the train travels in territory governed by a "stop" signal (at any speed), the emergency brakes will automatically be applied.

Train Operation—Door Control

The train operator is responsible for controlling the state of the passenger doors. The doors are to be opened when the train is stopped in the station to allow passengers on and off the train. The doors must not be opened at any other point in the system, for the protection of the passengers.

Door control is accomplished through the door control button on the left control stand. The state of the doors is indicated by the door indicator light (red when open) on the instrument panel and the control stand (redundant). Depressing the door control button while the train is stopped will control the state of the doors.

A safety system prevents the doors from being opened while the train is in motion—door control commands while the train is in motion will be ignored. If the train is stopped with the doors open, any attempt to move the train will cause a penalty application of the emergency brakes. In this scenario, both the door status light and emergency brake lights will be illuminated until the emergency brake is reset (as described in a previous section).

Train Operation—In-cab Signal System

In many rail systems using block signal technology, the signal information is available only on the wayside. This type of system presents two major problems: The operator has only one chance to see the signal, and the operator must remember the signal once it has been passed. Many contemporary locomotive cab designs include in-cab signals—devices in the cab which display the signal level of the block currently occupied. The Genesis-style (no preview) display is one such design, and the in-cab signals on the left of the display are replicas of the wayside signals for the current block (described above). The in-cab signal also provides a digital reading of both the signal speed limit and civil speed limit, both below the signal itself. The more restrictive of the two is the speed that must be obeyed, and this speed will be highlighted. A digital cab signal that flashes between a number and zero indicates that you should not go faster than that speed, and be prepared to stop. The preview displays have no in-cab signals, but rather display the effective speed limit over the entire previewed distance.

Train Operation—Acceleration and Braking Performance

Although there are many conceptual similarities between operating a rail train and driving an automobile, the biggest difference occurs in braking and acceleration performance. Because of the very large mass of a rail train (typically in the range of hundreds of tons), the distances required for acceleration and braking are much larger than might be expected. As the train speed gets larger, the stopping distance increases dramatically—a traveling speed of 150 mph requires more than two miles to stop.

This situation has several implications. An important safety consideration is that the large stopping distances make it virtually impossible for an operator to stop in time from high speeds for an unexpected track obstruction. The only reasonable solutions to this problem are to reduce the allowable train speeds in risk-prone areas, and to provide additional driving aids, such as obstruction warning systems. In general, operators are not held liable for situations which are beyond their control. In the simulation system, this issue is addressed by taking care that there are no unexpected hazards that are beyond the operator's control. There are no grade crossings (where cars or other trains might get stuck, presenting a collision hazard).

Another implication of large braking distances is the necessity for good judgment of braking points. Because the braking distances are so large, proper planning of braking points is essential for a train to be stopped accurately at stations (or other stopping points). This is a skill which requires a great deal of practice to master, and represents an important component of operator training programs in actual rail operations. Such training programs typically last for a year or more.

To shorten this learning curve, graphical representations of the train performance curves are shown in Figures A.3 through A.5. Figure A.3 displays the full-throttle acceleration profile on level ground. The speed is shown as a function of distance. From this curve, we can see that the distance required to reach 150 mph from a standing stop is approximately 3.2 miles.

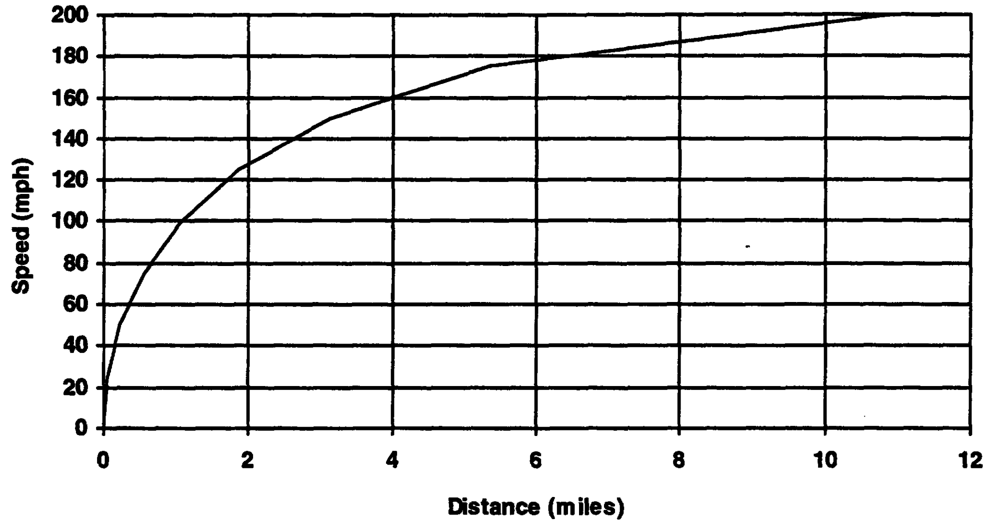


Figure A.3: Full-Throttle Acceleration Profile

In Figure A.4, the full-service braking profile is shown, again for the case of travel on level ground. To use this chart, read the distance associated with the speed to determine the stopping distance for that speed. From this curve, we can see that the braking distance from 150 mph is approximately 1.7 miles, which is substantially shorter than the distance required to achieve that speed in the first place (Figure A.3). The reason for this difference is twofold: a) Peak braking forces are generally higher than peak traction forces, for safety reasons, and b) at higher speeds, the resultant aerodynamic drag works against acceleration, but contributes to deceleration forces.

Figure A.5 shows the braking profile under emergency braking conditions. The distance required to brake from 150 mph under emergency braking is only about 0.68 miles. Because of the high rate of deceleration and resulting possibility of damage to the train and injury to the passengers, emergency braking is generally considered to be a last resort. For these reasons, penalty applications of the emergency brake—triggered by the alerter or ATP—should be avoided whenever possible.

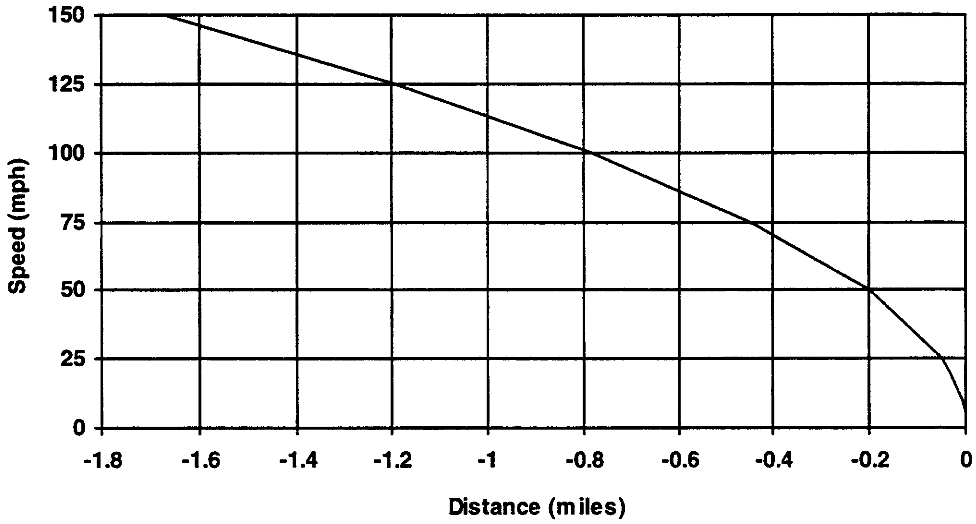


Figure A.4: Full-Service Braking Deceleration Profile

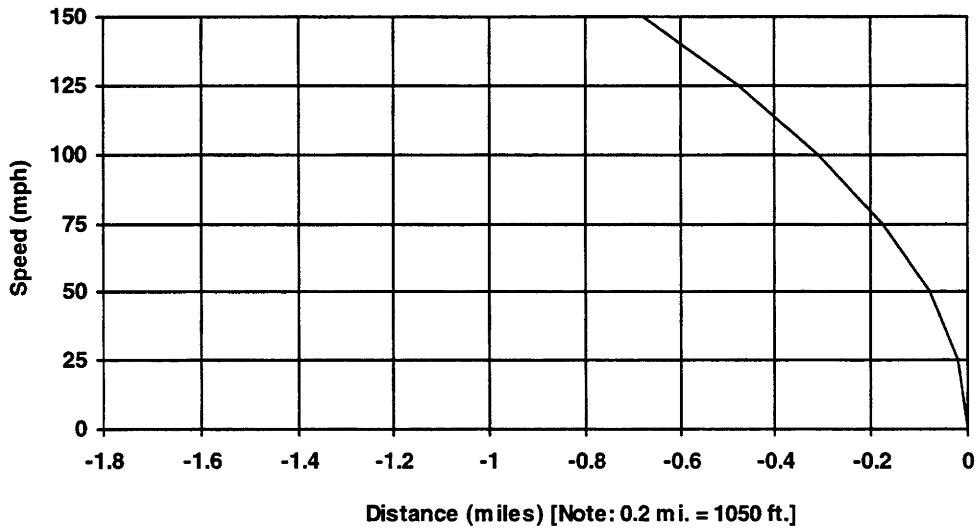


Figure A.5: Emergency Braking Deceleration Profile

System Operation—Schedules

During a shift of operation, you will make two round trips in the commuter rail operation. Each round trip starts at South Station in Boston, proceeds to Attleboro via Sharon and Foxboro, reverses direction on the Attleboro loop, and returns to South Station in Boston. Each trip leg (between South Station and Attleboro) is scheduled to take 60 minutes. When the train reaches the destination station, the train is stopped and the doors are opened, to allow the passengers on-board to disembark and allow new passengers to board. At the scheduled time, the operator should leave the station. In Attleboro, after the doors are opened to allow passengers to disembark, the train is then routed around the reversing loop to change direction. When the train arrives back at Attleboro in the opposite direction and comes to a stop, the doors are opened again allow new passengers to board. At this time, the instrument panel will be changed. At the scheduled time, the operator should shut the doors and leave the station to start the return trip to South Station. A printed schedule is provided to you at the beginning of each shift.

Under certain circumstances, there my be deviations from the prescribed schedule. In this case, it is the responsibility of the CTC to adjust the schedules accordingly. The train operator must wait for the CTC's instructions before departing a station at any time which is not in compliance with the prescribed schedule.

System Operation—Role of the CTC

The (CTC) manages the train movements in the rail system. S/he must monitor the positions and speeds (when possible) of the trains in the system, and adjust operating parameters of the system in order to achieve the system goals. The CTC also coordinates between the trains, as well as with "outside" agencies (such as fire, police, power, maintenance, etc.).

When there is a conflict between influences that govern the action taken by a train operator, the CTC is always the highest authority—train operators are required to follow all directions given by the CTC at any time.

System Operation—Operator Performance Requirements

In order to assure that you are capable of adequately controlling the train, your performance will be monitored throughout the test sessions. As an incentive, there is a bonus system which provides monetary rewards for good performance. If your performance does not fall within certain minimum criteria, penalties may be assessed. At the end of the experiment session, your performance is evaluated with regard to bonuses and penalties.

The Federal Code of Regulations, Number 49, Part 240, indicates that any willful violation of speed restrictions or signal indications is punishable with both a monetary fine and a loss of certification (which may be permanent or temporary, depending on the circumstances), which the engineers need to keep their jobs.

Because of these regulations, speed and signal compliance are considered key performance items. In the simulation system, violations are defined by ATP-induced or signal-induced penalty applications of the emergency brakes. During the road test period of the training phase, such a violation will result in your disqualification from further participation. In this case, you will be paid for the training period. During the experiment phase, the first violation in a shift will result in a penalty of 1,000 bonus points. If a second violation occurs in the same shift, you will be disqualified from further participation in the experiment. In this case, payment will cover the sessions that have been completed to date.

Other key operator performance items include station stopping accuracy and schedule deviation. In general, good performance in these areas will result in the award of bonus points, which result in an increase in payment for that session. The bonus point schedules are shown in Tables A.2 and A.3 and the penalty point schedules are shown in Table A.4.

Station Stopping Deviation	**Bonus Points**
more than 10m before stop point	0
$-10 \leq$ deviation < -8	14
$-8 \leq$ deviation < -6	28
$-6 \leq$ deviation < -4	42
$-4 \leq$ deviation < -2	56
$-2 \leq$ deviation $< +2$	70
$+2 \leq$ deviation $< +3$	56
$+3 \leq$ deviation $< +4$	42
$+4 \leq$ deviation $< +5$	28
$+5 \leq$ deviation $< +6$	14
more than 6m beyond stop point	0

Table A.2: Bonus Point Schedule for Station Stopping Accuracy

Table A.2 shows the bonus points that result from station stopping performance. The stopping point is defined as the first point at which the train stops, in the vicinity of the station. The closer the stop occurs to the designated stopping point, the more bonus points are awarded. The bonus points are distributed to favor undershoot (i.e., it's preferable to stop before the designated point than after it).

Schedule Deviation	Bonus Points
more than 60 seconds early	0
$-60 \leq$ deviation < -30	14
$-30 \leq$ deviation < -15	28
$-15 \leq$ deviation $< +15$	70
$+15 \leq$ deviation $< +30$	42
$+30 \leq$ deviation $< +60$	14
more than 36 seconds late	0

Table A.3: Bonus Point Schedule for Schedule Adherence

Table A.3 shows the bonus points that result from schedule adherence. In the case of an emergency or change in the speed limits between stations, the bonus points will be altered accordingly (e.g., if the speed limited is lowered by 50 mph for 10 miles, you will be given an extra 12 minutes to reach the next station).

Table A.4 show the penalties associated with poor performance and explicit violations of the operating rules. The most significant is a penalty application of the emergency brakes, resulting from either a speed violation (via the ATP system) or a signal violation. Both of these are considered serious offenses, and the penalty is substantial. The next penalty is for opening the passenger doors when the train is outside the station. This action is considered a serious compromise of passenger safety, and is penalized accordingly. The third penalty is for unnecessary use of the emergency brake. Use of the emergency brake takes a heavy mechanical toll on the train systems, and results in a very uncomfortable, and possibly dangerous, ride for the passengers. Gratuitous use of the emergency brake is inappropriate, and the penalty for unnecessary use is significant enough to outweigh any benefit that might be obtained (such as improving the station stopping or schedule accuracy). The fourth penalty is imposed if the operator fails to stop the train within the station. In this event, the doors must not be opened. In addition, the train operator must notify the CTC of the situation, and await further instructions from the CTC.

Infraction	**Penalty Points**
Penalty application of brakes (due to signal compliance or alerter violation)	-1750
Passenger doors opened outside of station bounds (more than 50 m under-/over-shoot)	-350
Unnecessary application of emergency brake	-175
Station overrun	-70

Table A.4: Penalty Point Schedule for Violations

After the total bonus points are computed for a shift, the bonus points are converted into a pay bonus at the rate of one dollar for each 100 points. There are a total of fourteen station stops during the two experimental round-trips. With 140 bonus points possible per station stop, there are 1960 bonus points possible, resulting in almost $20 extra pay.

Appendix B: High-Speed Rail Simulator Training—Review Quiz

The following set of questions was given to each subject as he/she began the training session to gauge his/her understanding of the tutorial material.

Simulator Operation Review

Instructions: For each question, circle the letter of the answer you feel best answers the question. There is only one correct answer per question.

1. "Mile posts" are located where?
   - a) on the wayside, at tenth-of-a-mile intervals
   - b) on all train instrument panels
   - c) on the wayside at mile intervals
   - d) on a monitor screen in the CTC operations center

2. Which of the following has the highest authority over the train operator's actions?
   - a) common sense
   - b) the CTC
   - c) the rail systems rules of operation
   - d) the wayside and in-cab signals

3. If the signal level of the upcoming block is APPROACH, what is the speed in that block (assuming the civil limit is 110 mph)?
   - a) 80 mph
   - b) 30 mph
   - c) 20 mph
   - d) 0 mph

4. What is the expected one-way travel time between South Station-Boston and Attleboro, including stops at the two intermediary stations?
   - a) 30 minutes
   - b) 90 minutes
   - c) 42 minutes
   - d) 2 hours

5. How many signal levels (i.e., wayside or in-cab signals) are used?
   - a) three
   - b) nine
   - c) eleven
   - d) four

6. How many control modes are available on the train?
   - a) one
   - b) two
   - c) three
   - d) four

7. When full-service braking is applied, what is the typical brake **cylinder** pressure?
    a) 110 to 130 psi
    b) 25 to 40 psi
    c) nominal (a few psi)
    d) 60 to 90 psi

8. Where are block signals located?
    a) at the entrance to every block
    b) in the middle of every block
    c) every half-mile
    d) on the back of the preceding train

9. What is the expected distance to accelerate to 150 mph from a standing stop on level ground?
    a) about 3.2 miles
    b) about 2.2 miles
    c) about 0.68 miles
    d) about 5 miles

10. Which category best describes the type of system being operated?
    a) elevated train
    b) subway
    c) commuter rail
    d) long-haul freight

11. Any brake display gauge that is above 140 psi indicates what?
    a) normal operation of that gauge
    b) the instrument panel needs to be adjusted to get the proper color
    c) that gauge's value is abnormal
    d) that gauge is broken

12. How is the cruise control disabled?
    a) only by depressing the cruise control enable button
    b) by entering a block with a lower speed limit
    c) only by manually applying the brakes
    d) either a) or c)

13. During system operation, how many trains are simultaneously in use?
    a) only one
    b) exactly two
    c) could be any number
    d) five

14. How is the cruise control enabled?
    a) by depressing the cruise control switch while braking to the desired speed
    b) by depressing the cruise control and door buttons simultaneously
    c) by holding the train at a steady speed under manual control
    d) by depressing the cruise control button while traveling at the desired speed

15. When will the ATP system cause a penalty application of the full-service brakes?
    a) At 180 mph
    b) 10 mph over the effective speed limit
    c) at 3+ mph over the effective speed limit (if maintained for more than 5 seconds)
    d) any speed over the effective speed limit

16. What is the purpose of the block signal system?
    a) tell the operator how many trains are allowed in that block
    b) so the train operator can determine the maximum allowable speed in that block
    c) to be sure the train operator is alert before entering that block
    d) to be sure the train operator is in contact with the CTC

17. In a block signaling system, how many trains are allowed to occupy a single block at the same time?
    a) one
    b) two
    c) three
    d) four

18. How many different braking modes are available to the train operator?
    a) one
    b) two
    c) three
    d) four

19. If the train operator attempts to move the train when the doors are still open, what will happen?
    a) the doors close automatically
    b) the alerter light is illuminated
    c) the emergency brakes are applied
    d) the passengers are warned over the intercom

20. What is the expected stopping distance from 150 mph to 30 mph under full-service braking on level ground?
    a) about 1.4 miles
    b) about 3 miles
    c) about 3.7 miles
    d) about 5 miles

21. What warning does the alerter system give the train operator before a penalty application of the emergency brakes is imposed?
    a) chime only, for 5 seconds
    b) electric shock through the seat, for 5 seconds
    c) flashing light only, for 15 seconds
    d) flashing light and chime, for 10 seconds

22. How does the train operator know the speed of the train?
    a) from the CTC
    b) from the speedometer on the instrument panel
    c) from the block signaling system
    d) from the traction gauge on the instrument panel

23. Where are CTC operators located?
    a) in a maintenance shed
    b) in small booths along the wayside
    c) in a centralized operations center
    d) in the last car of each train

24. What is the speed limit in and around a station (assuming the block signal is not "stop" or "restrict")?
    a) 70 mph
    b) 40 mph
    c) 30 mph
    d) it depends on the block signal

25. What is the maximum civil speed limit in the rail system?
    a) 110 mph
    b) it depends on the block signals
    c) 150 mph
    d) 180 mph

Appendix C: Train Schedule

The following page lists the train schedule used by the subjects in the preview display experiment. The stations listed in the schedule correspond to stations shown in the map accompanying the “Brake-Point Specification Worksheet” (Appendix E).

Train Schedule

Time	Station
00:05:00	Depart South Station
00:12:00	Arrive Sharon
00:12:30	Depart Sharon
00:25:30	Arrive Foxboro
00:26:00	Depart Foxboro
00:42:00	Arrive Attleboro (southbound)
00:42:30	Depart Attleboro (to loop)
00:44:00	Arrive Attleboro (northbound)
00:44:30	Depart Attleboro (for South Station)
01:00:30	Arrive Foxboro
01:01:00	Depart Foxboro
01:14:00	Arrive Sharon
01:14:30	Depart Sharon
01:22:30	Arrive South Station

Note: If you are behind schedule, you still must keep the train doors open for at least 30 seconds at each stop.

Appendix D: Exit Questionnaire

The questionnaire on the following page was given to the experimental subjects after the test sessions had been completed. The answers provided on this questionnaire were used to determine the subjective evaluation of the instrument panels.

Exit Questionnaire

1. Rate the displays in order of preference by placing a mark in the appropriate box:

	Liked very much	Liked	Neutral (didn't like or dislike)	Didn't like very much	Didn't like at all
no preview					
1.4 miles (fixed) preview					
3.4 miles (fixed) preview					
variable preview					

2. Rate the displays according to how difficult/easy it was to control the train:

	Controlling train was very easy	Controlling train was easy	Controlling train was not easy or hard	Controlling train was difficult	Controlling train was very difficult
no preview					
1.4 miles (fixed) preview					
3.4 miles (fixed) preview					
variable preview					

3. Do you feel that the training process provided adequate preparation for the test task?

____ adequate training

____ too little training Explain:

____ too much training Explain:

4. How much preview distance (if any) would make the task of train control easiest?

5. Any other comments? (Critical comments are appreciated. Feel free to make comments on the attached pictures.)

Appendix E: Brake-Point Specification Worksheet and System Map

The following sheet and attached system map were given to subjects to help them learn where to decelerate the train to reach the next speed limit successfully. All four pages were also found in the locomotive cab.

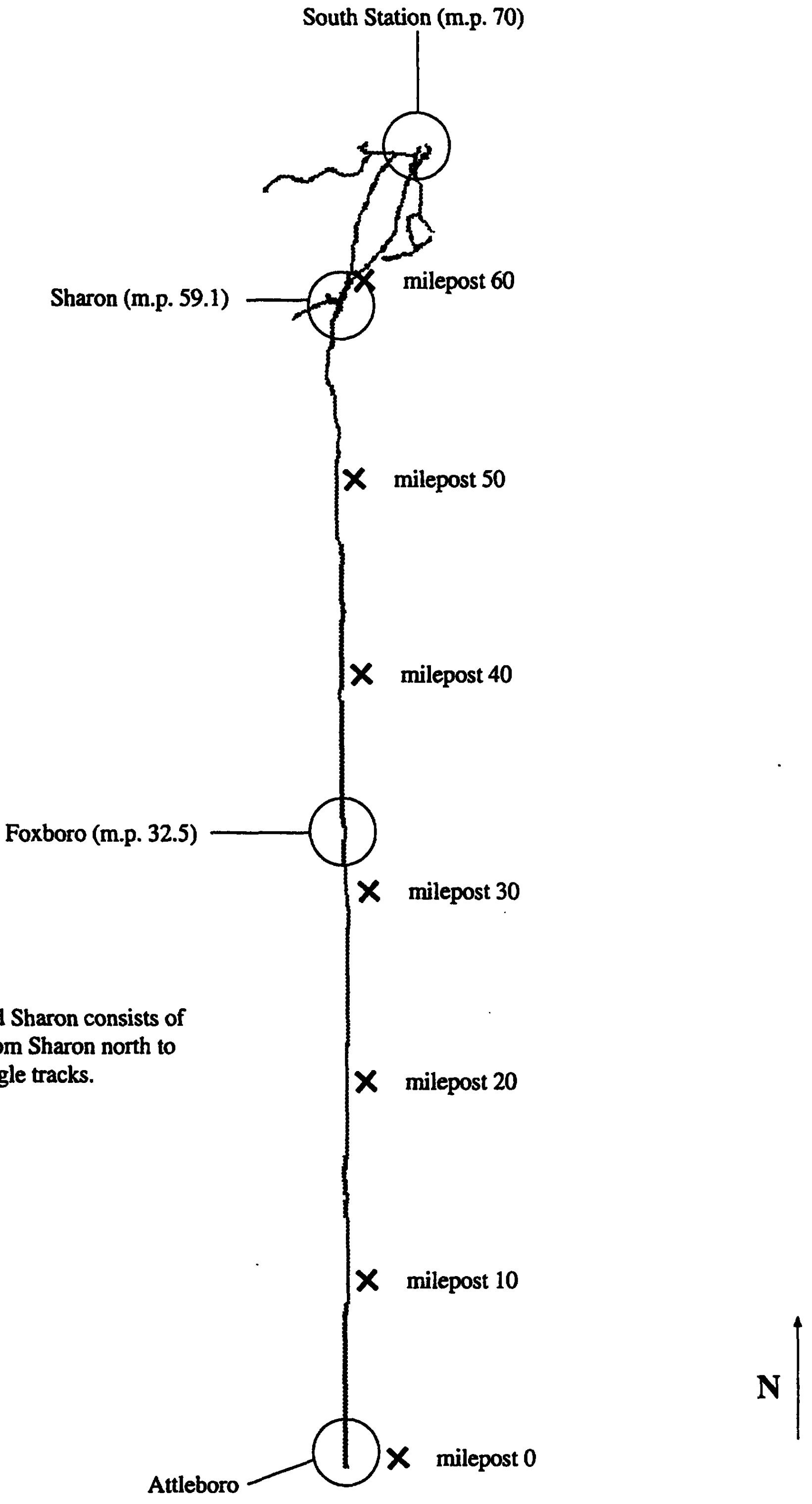
Brake-Point Specification Worksheet

The following table of speed limits and braking cues will help you decelerate in time to reach ensuing speed limits successfully, assuming all block signals are set to "clear" and full-service braking is utilized. See the attached "System Map" for track details.

Heading South out of South Station:		
Decelerate here...	**...to reach this speed...**	**...by this point.**
as you enter block 1537	17 mph	beginning of Sharon platform
as you enter block 812	17 mph	beginning of Foxboro platform
as you enter block 1375	17 mph	beginning of Attleboro platform
when you see the platforms at Attleboro again (after looping around)	17 mph	beginning of Attleboro platform (northbound)

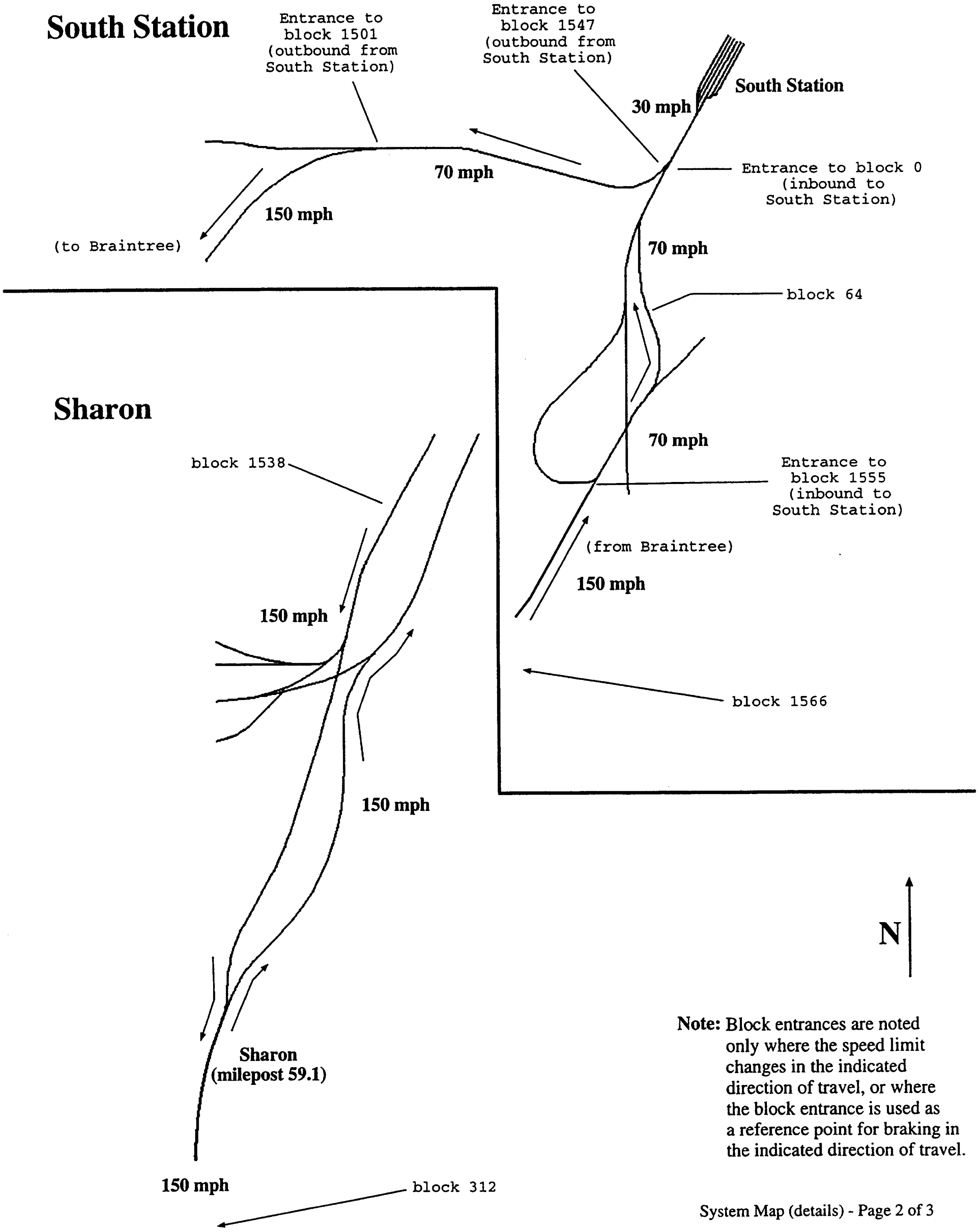
Heading North out of Attleboro:		
Decelerate here...	**...to reach this speed...**	**...by this point.**
as you enter block 838	17 mph	beginning of Foxboro platform
as you enter block 314	17 mph	beginning of Sharon platform
as you enter block 1566	70 mph	block 1555
as you enter block 64	30 mph	block 0
when you see the platforms at S. Sta.	17 mph	beginning of South Sta. platform

System Map



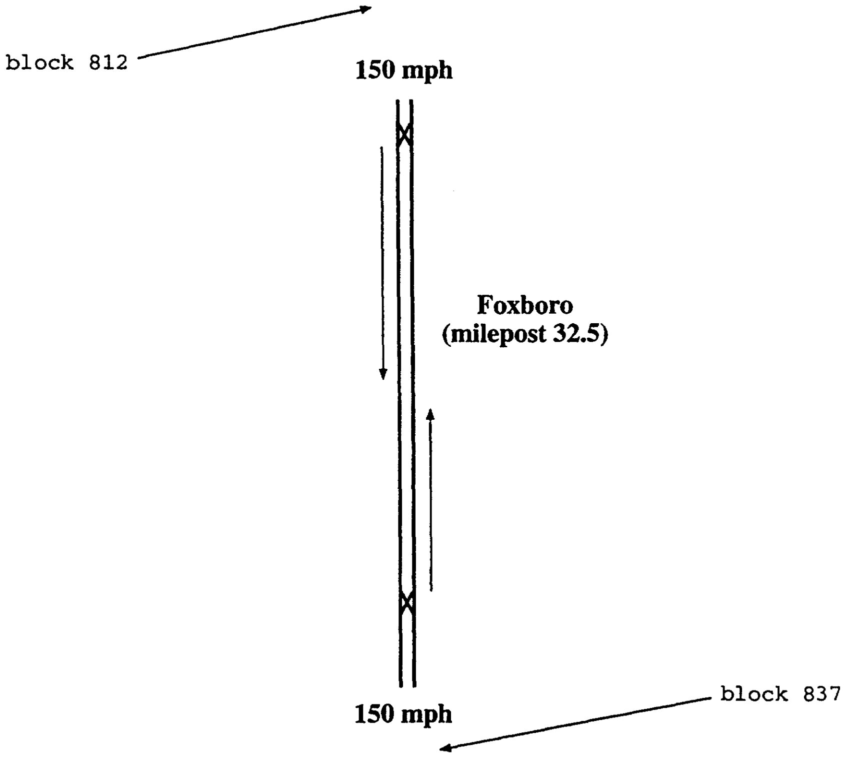
Note: Track between Attleboro and Sharon consists of two parallel tracks. Track from Sharon north to South Station consists of single tracks.

See pages 2 and 3 for blowups of the indicated regions (including wayside reference points and civil speed limits).

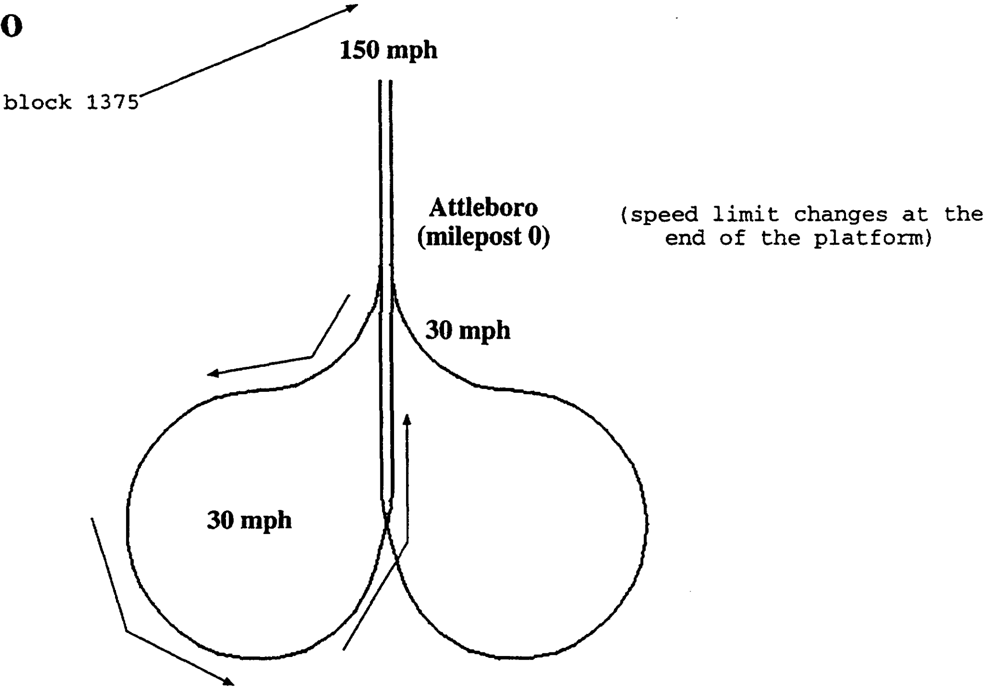


Note: Block entrances are noted only where the speed limit changes in the indicated direction of travel, or where the block entrance is used as a reference point for braking in the indicated direction of travel.

Foxboro



Attleboro



Appendix F: Future Considerations for the MIT/Volpe High-Speed Train Simulator

One of the secondary goals of this research project was to get feedback from Amtrak engineers about the realism of the MIT/Volpe Train Simulator. Though two students had previously received Ph.D.s using research performed with the simulator, those experiments were done with MIT students as subjects—no one with rail experience had previously used the simulator. Consequently, previous incarnations of the simulator utilized simplistic track networks and unrealistic control paradigms, such as an alerter whose time interval was independent of speed, fictitious signal systems, and penalty applications of the emergency brake.

Throughout the course of this experiment, we used two employees from the Volpe National Transportation Systems Center with prior rail experience as short-term pilot subjects (one round-trip each), one Amtrak engineer as a full pilot subject and three Amtrak engineers as experimental subjects. During and after each of these sessions, the subject's reactions to various aspects of the simulation were collected. In cases where the resulting changes would not significantly hamper future subjects' simulation experiences, or where the change was necessary for smooth operation of future subjects, those reactions resulted in immediate software changes. A plethora of comments, suggestions and critiques resulting from these experiments, however, have not yet been acted upon. Many of these suggestions would significantly enhance future simulations by making them as realistic as possible.

In general, several benefits can be derived by creating a track structure that is even more similar to one which the Amtrak engineers may be used to: First, less training would be required. The engineers would need the same amount of time to learn the operation of the simulation itself, but would not have to learn braking points and other reference cues. Second, the closer the simulation is to an actual rail environment (with respect to both the physical fidelity as well as to the system response to control inputs) the closer a rail engineer's actions will be to what they would be in the actual rail environment. One of the engineers verbalized that he would have driven differently had he known the territory better (e.g., he would not have been focusing on the display, but rather on the out-the-window cues; or he would not have been as worried about remembering the civil speed limits). Two of the engineers indicated that they preferred the preview displays over the no-preview display for the specific reason that it helped them better learn the unfamiliar territory. As discussed in the body of this paper, we are left wondering what their preference would have been had they already been familiar with the territory. Third, the higher the fidelity of the simulator, the greater the credibility that is lent to the results—both by the sponsors and by the public—and to the simulator itself. Of course, fidelity comes at a price, in terms of both human resources (in the form of software engineering experience) as well as capital resources (in terms of computational or graphics power).

Changes Needed to Increase the Physical Fidelity

According to one engineer, trains coast at idle, maintaining a constant speed, whereas the simulator loses a couple of mph per second at top speeds, ostensibly due to drag and rolling (track) friction. Maintaining constant speed at idle does not seem probable, and it is likely that the engineer simply needs better feedback regarding acceleration and deceleration. Each of the engineers also said that the acceleration of the simulator was too slow. The train dynamics in the simulation were based on the TGV short trainset and had last been updated in 1994. The acceleration and deceleration characteristics were tweaked after the first engineer subject, but the next two subjects also indicated that these traits were "sluggish." Future simulations should use acceleration and braking rates based on one of the locomotives Amtrak uses, preferably those that will be put into service at 150 mph in the coming years. This could be done by copying the operating characteristics out of manuals, though a better way may be to simply take a few rides on the trainsets to be mimicked and try to recreate the feel.

As the engineers use landmarks for remembering braking and speed reference points, the wayside objects should be more distinctive. Furthermore, if the sponsors hope to mimic a particular portion of track, the actual reference point from that portion of track should be used. This includes not only the wayside objects, but the block lengths and signals themselves.

There are several discrepancies related to the wayside signaling system that need to be resolved:

- Signal boards with numbers on them indicate a "distant" signal (i.e., that the train is approaching an interlocking).
- A "stop" signal on such a board indicates "stop and proceed" (with no further instruction).

- When there is a number on a signal, the number should be associated with a milepost (to 0.1 of a mile), not a block number.
- The supervisor of the engineers expressed that most Amtrak divisions are using “color” signals rather than “location” signals (though he said that all engineers should know the location signals).

At a switch, the signal needs to be placed before the switch, not after it. Also, at any crossover, the signal for the block going in the same direction on the parallel track (i.e., the block coming into the section of parallel track into which the engineer’s train is crossing) needs to be set to “stop,” indicating that no train on the parallel track can proceed into the section of track that the subject is about to enter. Also, the track itself needs to be drawn differently at the crossover, depending on which way the “frog” (the section of track that allows the crossover to occur) is attached. At 30 mph or so, the engineer will visually recognize which way the switch is attached to determine which direction the train will go in.

Furthermore, the signals should be spaced more like those in the mimicked track; or, at the very least, they should be spaced farther apart than they are currently. To change the locations of the signals in the simulation, which now are based on where road segments begin and end, would be difficult. The only way to alter signal locations presently is to change the minimum block length for a signal to be drawn, and this would only change the number of signals drawn, not the signals’ locations. The signal locations could be read in from a file, similar to the mileposts, and if there is no file, they could default to the way they are drawn now. However, then the signal locations would not coincide with road segment ends, which is how authorities are calculated. A new paradigm for calculating and enforcing signal territories will likely be quite time-consuming.

Two of the engineers said that the “clickety-clack” sounded like “flat” (i.e., worn) wheels, though they admitted that they sounded somewhat like jointed rail. Welded rail apparently does not make that type of noise. This should be investigated and, if need be, re-recorded.

The equalizing reservoir pressure should read the same as the brake pipe during release. The brake pipe should “follow” the equalizing reservoir.

One engineer mentioned that it was "strange" that there were no other trains in the system, but none mentioned the lack of cars at the grade crossings.

Changes Needed to Increase Fidelity of Train Control

During the course of the experiments, we uncovered many ways in which the train control paradigm of our simulator diverged significantly from what the engineers were used to:

When encountering a signal that is more restrictive than the previous signal, the engineer needs to acknowledge that signal by depressing a button (either a dedicated "signal acknowledge" button, or the alerter), regardless of the train's speed; if the train's speed is above that of the new signal, the brake system must be suppressed (i.e., a certain minimum amount of brake pressure must be applied) to avoid a penalty application of the full-service brakes. This suppression level may vary from one train to the next between 14 and 26 psi reduction. This is an easy change to implement in the software and would be a good first task for someone trying to learn the simulation.

The engineer normally is required to wait until the rear of the train has cleared a less-restrictive signal before accelerating beyond the old (more restrictive) signal limit. The train "length" needs to be defined, and the piece of code that checks the train's speed against the effective limit (in veh-2/atp.c) should take this into account.

The engineer must wait some period of time after stopping to allow the brake system to "recharge," or recompress adequate pressure in the brake pipe to stop the train. This recharging time may be less than a minute after a full-service application of the brakes, or more than a couple of minutes if an emergency application is given.

A train is not allowed to approach a bunker (the obstructing "pylon" at the end of a line) at more than 15 mph (civil limit). If there is no signal next to or above the bunker, the block approaching the bunker must be set to "restrict," as the bunker represents an obstruction in the track. If there is a signal next to or above the bunker, the signal for the last block approaching the bunker can be set to either "restrict" or "approach," either of which indicates that the engineer needs to be prepared to bring the train to a stop before the next signal. (The engineer who ran past the bunker may not have been helped by these restrictions, as he entered a 70 mph speed zone at 118 mph.)

These changes should be made in the permanent road databases and in the central traffic controller (CTC) software, which controls the signals of all trains attached to it.

The cruise speed should be controllable by the subject. That is, the subject should be able to key in, or dictate in some other way, a speed to which the system would then accelerate or decelerate. This is already implemented in the software, but needs to be activated and explained in the tutorial. There are several other changes (e.g., the alerter penalizing with a full-service application of the brakes instead of a penalty application, the ATP giving a buffer zone above the limit and penalizing with a full-service application only until the effective limit is achieved, etc.) that were made to make the simulator mimic, as close as possible, what the Amtrak engineers are used to. In general, these changes were implemented with command-line software switches, leaving the previous options intact as well. Though this system allows maximum flexibility when running the software, the proper command-line options need to be learned. Refer to the simulator training manual (at the Volpe Center) for more details.

Ways the Engineers' Control Behavior Differed From Expectations

The Amtrak engineers' control decisions based on signal levels was quite different than what had been expected. The engineers expressed that they might not give any application of the brakes right away (or at least not a very heavy application) when encountering a more restrictive signal. They generally know the distance (and thus the time) to the next signal as well as how restrictive that next signal could possibly be (i.e., the worst-case scenario) and can set their speed accordingly. Thus, the engineer might purposefully put the train in an overspeed situation (to save time, or to keep some brake pressure in reserve) when encountering a more restrictive signal. Though the speed and control input are recorded at regular intervals and later can be reviewed, the locomotive foreman explained that such control behavior did not reflect poorly in any way on the engineers. In an overspeed situation such as the one described above (approaching a more restrictive signal at a speed above the speed indicated by the signal), the engineer has five seconds to apply the brakes (at any level) before a penalty full-service application of the brakes is given. If the engineer applies the brakes before the penalty is applied, the penalty is averted. Some of the engineers seemed to operate the train in this way (i.e., braking slowly despite being above the speed limit indicated by the signal), though others did not (i.e., they observed the speed limit indicated by the signal).

If a light "drops in your face" (i.e., turns to red when the signal is already in your range of visibility), it most likely indicates a failure of the track circuitry, and is thus not necessarily treated as a complete emergency. If the operator can see the track ahead of him for a distance equal to or greater than the train's full-service stopping distance, he or she might just go to full-service braking, even if that would mean passing the red signal. However, if there is a siding or any other portion of the track that he can not see, the engineer will go to emergency braking just to be sure.

As mentioned before, several of the engineers expressed that they tend not to use full-service braking unless the situation requires it, as they like to keep some pressure in reserve in case of an emergency. Thus, the engineer would begin decelerating farther in advance than a full-service application would allow, but at a lower rate (maybe 13 to 16 pounds of reduction[29]). A couple of the subjects had trouble stopping at the stations accurately at first, due to this aversion to providing a full-service application of the brakes, but two of the three engineers performed satisfactorily by the end of the training (i.e., after being instructed that the system was designed to require a full-service application of the brakes). One engineer suggested that having the full-service braking curve on the preview display would encourage risk-taking, and suggested having a "14-pound reduction" curve instead. The engineer who did not perform satisfactorily had to resort to the emergency brakes for three of the station stops, and actually crashed through the bunker at South Station at 20 mph.

The locomotive foreman suggested that we gather data on the acceleration and deceleration forces exerted on the train (as the IITRI simulator does) and penalize the subjects accordingly, as this constitutes a major part of their training. In particular, the engineers are trained to avoid using full-service brakes when stopping at a station, to avoid jolting the passengers. Collecting this data is a straight-forward task, but conveying the forces generated in braking and

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[29] Engineers talk about the amount of braking force applied to the wheels in terms of "pounds." They are referring to the pounds per square inch, or psi, of brake pressure that is exhausted from the brake pipe during a brake application. A pressure equal to this "reduction" is applied to the brake shoes. The maximum possible service application of brakes varies between 24 and 29 pounds, depending on the train, with zero pounds (or "no reduction") corresponding to no application of the brakes.

acceleration may be difficult if these characteristics are not what the engineers are used to.

General Suggestions

Several subjects requested an indication of the “cruise set speed” on the preview displays when cruise control is active.

Subjects’ performance might benefit from an audible indication of a change in the preview display status. The engineers are used to allocating their attention out the window (usually the side window), looking for reference points and thus need a cue to check the preview display more frequently. However, at least one of the engineers also expressed that he relies heavily on the in-cab signals and thus checks the cab displays relatively frequently.

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