Design and Evaluation of Decision Aids for Control of High-Speed Trains: Experiments and Model

by

Shumei Yin Askey

Submitted to the Department of Mechanical Engineering in Partial Fulfillment of the Requirements for the Degree of

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Submitted to the Department of Mechanical Engineering on 23 May 1995 in partial fulfillment of the requirements for the Degree of Doctor of Philosophy in Mechanical Engineering

Abstract

The objective of this research was to develop computer-based decision aids for control of high-speed trains wherein the human driver is in charge, and to investigate the impact of these aids on safety and operational efficiency. In particular, this research sought to design and evaluate decision aids for drivers to compensate for human limitations in signal detection and information processing that are hard-pressed by high-speed locomotion. Three concepts of aiding, referred to as preview aiding, predictive aiding, and advisory aiding, were proposed, then implemented in a high-speed rail system simulator as integrated cab displays with level of aid graded from low to high. The three displays are referred to as the preview display, the predictor display, and the advisor display. Each level of display incorporated a superset of the aiding cues implemented in the next-lower level. A conventional high-speed train cab environment was implemented as a baseline for comparison purposes and is referred to as the basic display.

Formal human-in-the-loop experiments were conducted to evaluate effects of these displays on driver-train system performance. Preview aiding was found to improve situation awareness—the subjects' reaction time to an unexpected signal change being reduced from 8.6 sec with the basic display to 1.4 sec with the aided displays. Predictive aiding improved the subjects' decision to use braking systems and, therefore, offers the promise of increased safety. The advisory aiding was found to reduce total cost (energy consumption plus a weighted schedule deviation) by up to 11% with respect to the basic display on a simple experimental track. The display aids were also found to significantly improve both station-stopping accuracy and schedule adherence. A simulation with a rule-based driver model confirmed the improvement in performance observed with the predictor display. The extra information in the aided displays increased "head-down" time. The extra information, however, was not found to overload subjects. In fact, subjects rated the advisor display as imposing the lowest overall workload and preferred it as their first choice to the basic or the predictor display.

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GLOSSARY†

Alert system—An onboard safety system, also called a "deadman system", that generates a warning at random periods to call for the driver's attention. Once the warning is active, a mechanism should be touched or pressed by the driver to acknowledge and silence it. The purpose of such an alert system is to monitor whether the driver is alive and mobile during the operation of the train. In this research, a keyboard key is pressed to acknowledge the alert system.

ATP—Automatic Train Protection. In general rail terminology, it is the portion of an automatic train control system that ensures safe train movement by a combination of train detection, train separation, overspeed protection, and route interlocking. In the context of this report, it specifically refers to the portion of its function that prevents movement at speeds in excess of allowed limits.

Automatic interlocking—An interlocking controlled by circuit logic so that changes or movements of signals, signal appliances, and track switches follow each other in proper sequence without need for manual control, thus permitting train movements along routes only if safe conditions exist.

Block—A length of track of defined limits, the use of which by trains and engines is governed by block signals, cab signals, or both.

Block signal—A fixed signal at the entrance of a block to govern movement of trains entering and using that block. This signal conveys automatic block aspects (color combinations of signal lights) to train operators, thereby indicating allowed speeds.

Cab—The section of the power car of a trainset where the driver works.

Cab signal—A signal located in the engine control compartment or cab indicating a condition affecting the movement of train or engine and used both in connection with interlocking signals and in connection with or in lieu of block signals.

† Rail terminology adapted from [Luedeke 1992].
Civil speed—The maximum speed allowed in a specified section of track or guideway as determined by physical limitations of the track or guideway structure, train design, and passenger comfort.

Dispatcher—The person who monitors and controls the routing (meets, passes, and so on) of trains.

Dynamic braking—A method of braking in which the motor is used as a generator and the kinetic energy of the apparatus is employed as the actuating means of exerting a retarding force.

Emergency—a condition which could cause bodily harm or severe physical injury to persons, or serious damage to equipment, or both.

Emergency braking—Irrevocable open-loop braking to a complete stop, at the maximum safe braking rate for the system (typically a higher rate than that obtained with a service brake application).

Emergency braking distance—The distance on any portion of any railroad which any train operating on such portion of railroad at its current speed will travel during an application of the emergency brakes. It is measured from the point where emergency braking is initiated to the point where the train comes to a stop.

Emergency stop—The stopping of a train by an emergency brake application which, after initiated, cannot be released until the train has stopped.

External environment—Anything external to a given trainset (e.g., wayside signal, object on track, heavy wind, and so on).

Failure—the inability of a system or component to perform its required functions within specified performance requirements.

Full-service braking—the maximum amount of non-emergency braking that can be applied to the train.

Full-service braking distance—the distance on any portion of any railroad which any train operating on such portion of railroad at its current speed will travel during a full-service application of the brakes. It is the distance from the point where full-service braking is initiated to the point where the train comes to a stop.
**Grade crossing** — A combination of two or more highways, railroad tracks, pedestrian walkways, or other fixed guideways intersecting at the same level.

**Guideway** — The surface or track, and the supporting structure, in or on which vehicles travel and which provides lateral control.

**Headway** — The time separation between two trains traveling in the same direction on the same track, measured from the instant the head end of the leading train passes a given reference point until the head end of the train immediately following passes the same reference point.

**High-speed** — Velocity of at least 198 km/h (125 mph).

**High-speed rail** — A rail transportation system which operates at speeds in excess of 198 km/h (125 mph).

**Interlocking** — An arrangement of signals and signal appliances so interconnected that their movements must succeed each other in proper sequence and for which interlocking rules are in effect. It may be operated manually or automatically.

**KP** — Kilometer post. The counter of distance from the origin station in kilometers.

**Maglev** — Magnetic levitation. Levitation of vehicles by magnetic force either by magnetic attraction or repulsion. The term is usually used to describe a guided transportation system using magnetic levitation and guidance.

**Overspeed** — In excess of maximum allowable safe command speed.

**Pantograph** — A current-collecting apparatus having a long contact shoe which glides perpendicular to the underside of an overhead contact wire of the power car.

**Regenerative braking** — A form of dynamic braking in which the kinetic energy of the motor and driven machinery is returned to the power-supply system.

**Service braking** — Any non-emergency brake application of the braking system.

**Speed profile** — A plot of speed against distance traveled.

**Switch** — A pair of switch points with their fastenings and operating rods which provides the means for changing a route from one track to another.

**Wayside signal** — A signal of fixed location along the track right-of-way.
To Richard
I hear and I forget. I see and I remember. I do and I understand.

—A Chinese proverb
CHAPTER ONE

INTRODUCTION

1.1 ISSUES

High speed rail technology offers great promise for future intercity passenger transportation. The advantages of high-speed rail systems have been demonstrated in European countries and in Japan with their successful operation for almost two decades.

1. Energy consumption per passenger-kilometer in high-speed rail is more economical than that of other forms of transportation, both road and air. While accounting for 23% of goods traffic and 9% of passenger traffic within the European Community, high-speed rail only consumes 3% of energy expended in the field of transportation. In comparison with automobiles, high-speed trains consume half as much energy per passenger-kilometer at twice the speed. Similarly, in comparison with modern aircraft, high-speed trains consume half of the energy over similar distances (and with comparable occupation rates) [International Union of Railways 1992].

2. From an environmental standpoint, high-speed trains occupy small landtake: on average, they use between a third and a half the space required by an expressway; a two-track railway has a capacity similar to that of a six-lane highway. In addition, high-speed trains do not generate major noise disturbance, especially if the noise exposure time is taken into account.
3. From the perspective of operational efficiency and social cost, high-speed rail reduces time overhead associated with travel. Time spent traveling to and from airports, which are usually located far from city centers, can be saved by the use of high-speed trains—since train stations can be located more centrally in the cities.

The desire for faster means of transportation, advanced technology, and the success of existing high-speed rail systems have propelled train speeds to a high level—currently in the range of 200 to 320 km/h (124 to 199 mph); and the speeds continue to increase. Several countries have already experimented with Maglev systems with potential speeds far greater than conventional wheel-on-rail systems (up to 500 km/h, or 311 mph).

As train speeds increase, prevention of accidents gains emphasis. Higher speed means greater kinetic energy in any collision and therefore exacerbates the severity of an accident. As pointed out by a study on collision avoidance and accident survivability [DOT/FRA 1993], "...collision at high speed, over 200 km/h (125 mph), would result in severe damage to several vehicles or vehicle sections, and multiple fatalities. These results suggest that it is not possible to ensure survivability in high speed collision with any reasonable vehicle design philosophy, and the safety emphasis in High-Speed Guided Ground Transportation (HSGGT) systems must be on the avoidance of such accidents."

One of the many issues to be addressed to ensure complete prevention of accidents is the human factors associated with the driver’s functions within high-speed trains. Assuming a human driver is responsible for the control of the train, design of the driver-cab interface and signaling systems should deal with the following effects of high speed on human performance:

1. High speed reduces the allowable time for the driver to respond to unexpected events and, therefore, poses greater demands on the driver to anticipate or to be aware of potential dangers and be able to make quick and appropriate control decisions.

2. High speed makes it more difficult for the train driver to see any wayside signals or other objects at the wayside with other visibility factors being the same. In fact, one high-speed train operator, the French Société Nationale des Chemins de Fer Français (SNCF), has determined that the maximum speed for accurate driver perception of wayside signals is 220 km/h (137 mph) [DOT/FRA 1991].
These problems, along with minimum stopping distances of 4 to 5 kilometers (2.5 to 3.1 miles) for operation at 300 km/h (186 mph) [DOT/FRA 1991], dictates the necessity of a driver-cab system design that fully considers the impacts of human factors.

One seemingly apparent solution is to design a fully-automated system—completely replacing the human functions by automation. Although full automation of high-speed trains can be realized given the modern technology of measurement, control and computers, the human driver is still necessary in operating a high-speed train for the following reasons:

1. To handle the unexpected. It is still neither economically nor technically possible for a computer to control a train for all conditions, including unexpected events. The human is still the ultimate source capable of the reasoning and creativity necessary for handling situations that are difficult or impossible to anticipate.

2. To take over control in case of automation failure. When confronted with predictable and repetitive situations, any human operator, no matter how responsible, will be more fallible than an automated system. However, automation may fail; when it does, it is the human's responsibility to take over control.

3. Public anxiety. The general public is still hesitant to board a train that would run as fast as 300 km/h with no human driver. No doubt, there would be great public anxiety with driverless control in full-size high-speed trains. Driverless systems do exist, however, in the form of small-scale trains that operate within airports (e.g., Dallas - Fort Worth) or from airport to city center (e.g., the French VAL), indicating that reflex anxiety about driverless trains may be waning.

4. Liability in case of an accident. The threat of litigation, in case of any accident in an automated system, gives developers pause.

5. Political factors. Generally associated with the legal issues and public resistance, political decisions in a democratic society usually reflect the public opinions.

Therefore, human operators remain in the cab of current high-speed trains. However, keeping the human as part of the high-speed train control system requires thorough investigation of possible means for aiding the human driver (and allocating functions between human and machines) to achieve the desired safety and operational efficiency.
1.2 OBJECTIVES

Two major approaches can be identified in redesigning the functions of the human driver. More automation is one option. The human operator then becomes a supervisor of the automatic system by monitoring the automation for failures and fault diagnosis. An alternative to this machine-in-charge approach is to compensate for the sensory, perceptual and cognitive limitations of the human operator with various aids, while keeping the human in control.

Both of the above approaches have potential problems. Concerns associated with increasing automation include possible loss of manual skill and possible loss of situation awareness [Endsley and Kiris 1994]. In highly automated systems, operators are likely to be out-of-the-loop and handicapped in their ability to take over manual control when automation fails or in the event of an incident. In contrast, the problem with increasing sensory, memory, and decision aids is that at some point operators may be overloaded and “killed with kindness.” They would not be able to allocate their attention appropriately among all the information sources and the task at hand. As a result, their performance in signal detection and decision making deteriorates.

The objective of this research was to develop computer-based decision aids for control of high-speed trains where the human driver is in charge, and to investigate the impacts of these aids on safety and operational efficiency. In particular, this research sought to design and evaluate decision aids for drivers in order to compensate for human limitations in signal detection and information processing that are hard-pressed by high-speed locomotion.

Under this objective, three concepts of aiding—preview, predictive, and advisory aiding—were proposed and realized experimentally as cab displays with increasing levels of aiding. It had been proposed to explore the effects of these displays on driver-train system performance. In particular, the research tried to answer questions of what information should be presented and what aids should be provided to the driver in view of human limitations in performing the task of high-speed train operation. In addition, issues of how the aiding information should be organized and presented to the operator as an effective decision support were addressed via integrated cab displays whereby the aids were implemented.
1.3 BACKGROUND

1.3.1 Design of Decision Aids for Drivers of High-Speed Trains

A prerequisite for achieving higher speeds in rail systems has been significant changes in signaling equipment. As such, aiding for high-speed train operators has focused on novel forms of cab signaling. In current high-speed train systems, the design of signal systems and human-machine allocation differ significantly with respect to the degree of automation implemented in these systems. Operation of the German *Inter-City Express* (ICE), for example, is considerably more automated than operation of the French *Train à Grand Vitesse* (TGV). It is, in fact, appropriate to say that an ICE driver is more a supervisor of automation than a direct manual controller. In contrast, manual control is the prevailing operation mode on the TGV with computer monitoring and assistance [DOT/FRA 1991].

Both systems rely on some data transmission techniques to transmit information necessary for speed control from the wayside to the cab. Information transmitted to the ICE (once every second, for automated control) includes distance to next stop, braking curve†, the traveling direction, target speed in 5 km/h (3.1 mph) increments, target distance, line gradient, and civil speed restrictions. All the above information is used for automatic control under normal situations. In case of automation failure, the human would take over control [Sheridan et al. 1993].

In comparison, information on the TGV Atlantique is not as rich as that on the ICE. The signaling system on a TGV Atlantique provides to the cab the maximum speeds in the current and next blocks (block length is about 2 km), absolute stopping points, and power cable pantograph up or down commands.

1.3.2 Evaluation of Decision Aids Via Experiments

One approach to evaluating decision aids is by use of human-in-the-loop experiments, which are generally complex and difficult to design and control. One of the difficulties is the large number of parameters involved. A second difficulty is in determining which parameters should be held fixed, which ones should be varied, and over what range. A

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† Calculated at a wayside control station and transmitted to onboard automatic control system.
third problem is that the participation of human decision makers in the experiment precludes the execution of a large number of trials. It is clear that an evaluation study is a large and very time-consuming activity.

Few papers in the related literature can be found on designing or evaluating decision aids for high-speed train drivers. Kuehn [1992] reports a human-in-the-loop experiment evaluating effects of an Advanced Train Control System (ATCS) display on train handling and compliance with operating rules by the locomotive engineers. He compared three means of information presentation to the driver: (1) an ATCS display that constitutes a speed prediction (for one point in the future) given current control settings and the effects of grade, (2) an alternative display that does not contain prediction of speed but shows feedback on the track crossings, braking systems, and other in-train force management indications, and (3) conventional track warrants with a printed track profile. Results show that, with ATCS, subjects were less likely to exceed speed limits because of two distinctive features of the display: (a) the speed prediction and (b) an impending penalty brake associated with the predicted speed. Haga [1991] provides practical suggestions on what to display in the cab for a moving block signaling system using satellite communication, which allows much closer distances between trains without compromising on safety. He proposed a display layout but no literature has been found on its experimental evaluation.

1.3.3 Evaluation of Decision Aids Via Model Simulation

An alternative method to human-in-the-loop experiments in evaluating decision aids is computer simulation using mathematical models of human decision making. The main advantages of simulation study of decision aids with human models are as follows: (1) They provide a precise and quantitative formulation of task aspects such as goals, system dynamics, and basic concepts of human functions. Therefore, models potentially have predictive capability, rendering a basis for selecting design alternatives. (2) Models provide a flexible tool to systematically analyze effects of aiding on system performance. (3) They allow prediction of system performance under various information displays to be achieved in shorter time and at lower cost. As such, models may be used to provide early and preliminary evaluation of competing configurations without the necessity for expensive human-in-the-loop experiments. (4) In later stages of display development, models can serve as powerful diagnostic and extrapolative adjuncts to the necessary human-in-the-loop experiments.
While machine system dynamics are generally easy to obtain, creating a simulated human model that can perform the control tasks has been a challenge in the human-machine-systems research domain.

There have been numerous engineering models of the human operator. Of particular relevance are those of systems where the human is in control. Early models of the human operator in manual control tasks took the form of a servomechanism in a compensatory system. In such models, the human operator has a signal input—the difference between actual system response and the reference input. A successful model of this type in the frequency domain is the simple crossover model [McRuer et al. 1965]. These models have been used in a variety of engineering and research applications including the design of controls and displays [Sheridan and Ferrell 1974].

Few real-world situations involve just the simple manual tracking tasks with compensatory displays where the operator is assumed to observe only an error variable. In fact, the operator may be presented with both input and output variables separately and independently, which is the so-called pursuit display. Although models of pursuit-tracking have not enjoyed as much success as those of compensatory tracking, experiments have shown repeatedly that pursuit tracking is easier to learn and generally results in smaller error than compensatory tracking [Sheridan and Ferrell 1974].

More characteristic of every day tasks than pursuit or compensatory control is preview control where the human operator has available a true display of the reference input from the present time until some time into the future. Preview tracking has been modeled by dynamic programming [Sheridan 1966] and by optimal control techniques [Miller 1967, Tomizuka 1973].

A systematic and extensive effort in the optimal control-theoretic approach of modeling the human operator can be found in a series of studies conducted by Baron and his colleagues [Baron and Kleinman 1969], and has been applied to manned-vehicle systems [Elkind et al. 1968, Kleinman et al. 1971]. The basic optimal control structure has been extended to multivariable systems with monitoring and decision-making tasks [Baron 1976; Kleinman and Curry 1977; Wewerinke 1981], and to systems of multitasks of different objectives or supervisory systems [Muralidharan and Baron 1980, Baron et al 1980]. It has also been applied to ship handling [Wewerinke and Tak 1988], to navigation [Papenhuijzen 1988; Sutton and Towill 1988; Salski et al. 1988; Papenhuijzen and Stassen 1992], to car driving [Levison 1993], to manned robotic systems [Wewerinke 1991], and to display studies in
aviation [Baron and Levison 1975 and 1977, Hess 1977, Johannsen and Govindaraj 1980]. Models in these studies all bear an implied assumption: that the human's control behavior is compensatory, i.e., that control decisions are made based on instantaneous error instead of a preview of future inputs which is a critical behavior of a vehicle driver (see Section 2.2 for detailed discussion). A model of a train driver is not yet available or known to the author.

1.4 APPROACH

As mentioned earlier, this research proposed three types of aiding—preview, predictive, and advisory aiding—for control of a high-speed train under the assumption of complete manual control. The aiding was based on a system analysis of an operator's driving behavior under high-speed locomotion, and on understanding effects of these aids on driver performance in view of the human's limited capabilities.

To evaluate the effectiveness of these aids, the three types of aiding were implemented as cab displays with aiding levels graded from low to high. A no-aiding display, referred to as the basic display, showing the standard cab signals and environment interface indicators inside a cab, was also implemented. With the basic display as a baseline for comparative evaluation, each of the proposed displays included the indications of the previous level of display. In particular, the display of the first aiding level, referred to as the preview display, shows not only the indications provided in the basic display, but also previews of civil speed limits, signal aspects, track geometry, and so on for up to 20 km ahead. The display of the second aiding level, referred to as the predictor display, shows three predicted speed profiles overlaid on top of the preview display. Similarly, the display of the third aiding level, referred to as the advisor display, shows a minimum-energy speed profile† of the present trip overlaid on top of the predictor display.

Such an inclusive design and implementation of the displays allows the investigator (1) to address the concern that drivers may be overloaded with increased aiding, (2) to isolate effects of each type of aiding and thereby provide insight on the use of these aids, and (3) to demonstrate how the proposed aids could be presented and implemented.

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† Minimum under the constraints of schedule, speed limits, passenger ride quality, and the locomotive's braking and traction capability.
Formal human-in-the-loop experiments were conducted to investigate effects of these aids on driver-train system performance. Since preview is the backbone of the predictive and advisory aiding, a preliminary human-in-the-loop experiment was first performed to validate the preview aiding. This experiment aimed to compare the effects of the preview and the basic displays. It was expected that the preview display would improve situation awareness and reduce workload. In addition, measures of operation efficiency, such as schedule adherence, station-stopping accuracy, and energy consumption were expected to improve with the preview display.

The main experiment was conducted to fully investigate effects of the predictive and advisory aiding on system performance. In particular, this experiment compared effects of the basic, the predictor, and the advisor displays on performance. It (1) addressed the issue of potential overloading or "killing with kindness" due to more information being provided to the driver than can be assimilated, (2) investigated effects of predictive aiding on decision making, (3) evaluated effects of advisory aiding on energy consumption, and (4) assessed effects of the aids on situation awareness and measures of operation efficiency such as station-stopping accuracy, schedule adherence, and passenger ride quality.

In terms of experimental facilities, a flexible driver-train simulation system was developed for this research. A "virtual" driver-cab environment was created using computer-generated display of the track scene ahead. The "train" had the true dynamics of a passenger train and a control mechanism for traction and braking. A summary description of the experimental simulator facility is provided in Appendix A. The advantages of such an experimental simulator are twofold: (1) relatively low development cost and even lower cost of maintaining or "remodeling" such systems, and (2) the flexibility for configuring various designs of driver-cab interface for experimental investigation.

The experiments were conducted with university students as test subjects. "Naive" subjects have the advantage of having equal exposure to all experimental conditions, whereas expert subjects might be most comfortable in the condition that most closely resembles their daily experience.

The proposed aids were further investigated with a model-in-the-loop simulation. A normative rule-based driver model was developed and applied to demonstrate effects of the proposed aids on safety and operational efficiency.
1.5 THESIS OVERVIEW

This report documents the design of the decision aids and experiments done to evaluate their effects on driver performance in control of high-speed trains. Chapter 2 discusses the underlying considerations in proposing the preview, predictive, and advisory aiding, and presents the corresponding cab environment displays that realized these aids. Chapter 3 first summarizes the results of a preliminary investigation of the preview aiding, then reports and discusses in detail the experimental evaluation of the preview, predictive and advisory aiding in the form of the predictor and advisor displays. The simulation with a driver model, the alternative method of evaluation of the aids, is presented in Chapter 4. The conclusions in Chapter 5 summarize the major results and contributions of this work, discuss implications of these studies for driver-cab interface design of high-speed trains, and provide directions for future research.
CHAPTER TWO

DESIGN OF DECISION AIDS

2.1 OVERVIEW

This chapter starts with a background description of the functionality of rail signals which helps in understanding the rationale underlying the design of the decision aids. Then the chapter proceeds with an analysis of an important driving behavior, which leads to the development of a paradigm of high-speed train speed control. The paradigm classifies the information necessary for safe speed control into two categories: (1) the preview information that the driver needs to form a desired target speed, and (2) the feedback information that provides instantaneous error between the desired target speed and the current speed. Effects of high-speed locomotion on human preview capability are then discussed. Implications of these effects and requirements on designing decision aids in cab-driver interface are presented.

A conventional practice of cab signaling and information presented to a driver of a high-speed train is implemented as the basic display. Three types of aiding are proposed based on the analyses of the driver's task and behavior in driving a high-speed train. Three corresponding displays are then implemented for experimental evaluation.
2. RAIL SIGNALS

This section provides preliminary background on the functionality of rail signals, which is important for understanding the rationale behind the design of the aids. The explanation is based on a 6-block 7-aspect signaling system that is currently implemented in the high-speed rail system simulator (Appendix A) and was used in the experiments. It should be noted that real implementations of rail signals vary from system to system, though the fundamental functionality of signals in a block signaling system is similar.

Figure 2.1 illustrates the 6-block 7-aspect block signaling system. The 7 aspects (or color combinations) are GGG, GYG, YGY, YYY, YRY, RYR, and RRR (G—green, Y—yellow, or R—red), progressing from "no restriction" (train may go as high as the civil speed limit allows) to "stop" (must stop before this set of lights). Associated with each signal aspect is a signal level or signal speed. The signal speeds used in this research are listed in Table 2.1.

![Table 2.1 Signal Aspects and Signal Speeds](image)

<table>
<thead>
<tr>
<th>Signal Aspect</th>
<th>Signal Speed (km/h)</th>
<th>Definition of the Aspect</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>GGG</strong></td>
<td>300</td>
<td>Proceed</td>
</tr>
<tr>
<td><strong>GYG</strong></td>
<td>300</td>
<td>Proceed approaching next signal at 270 km/h</td>
</tr>
<tr>
<td><strong>YGY</strong></td>
<td>270</td>
<td>Proceed approaching next signal at 220 km/h</td>
</tr>
<tr>
<td><strong>YYY</strong></td>
<td>220</td>
<td>Proceed approaching next signal at 160 km/h</td>
</tr>
<tr>
<td><strong>YRY</strong></td>
<td>160</td>
<td>Proceed approaching next signal at 80 km/h</td>
</tr>
<tr>
<td><strong>RYR</strong></td>
<td>80</td>
<td>Proceed preparing to stop</td>
</tr>
<tr>
<td><strong>RRR</strong></td>
<td>0</td>
<td>Stop, do not enter.</td>
</tr>
</tbody>
</table>

* G—Green, Y—Yellow, R—Red.

Rail signals may be readily explained with an analogy to familiar highway signals. A car's motion on a highway is governed by speed limits and traffic lights. The speed limits (indicated by signs posted on the side of the road) are static, while the traffic lights change dynamically to prevent collision with crossing traffic. Similarly, a train's motion on a rail track is governed by civil (nominal) speed limits and rail signals. The civil speed limits are determined by physical limitations of the track, train design and passenger ride quality, and
are static, while rail signals may change dynamically to prevent collision with a train, an
obstruction, or maintenance crews on the same track.

The prevention of a collision is achieved by dividing the track into blocks with each having
a signal either fixed at the entrance of the block or displayed inside the cab. The use of a
block by trains is governed by the signal aspect (color combination) of the block. Rail
signal aspects, like traffic lights on a highway, serve to prevent collisions. On a highway,
the temporal sequence of Green—Yellow—Red of a highway traffic light tells a car driver
to prepare to stop when seeing a yellow light ahead because the next level of signal (after a
few seconds) will be Red (meaning "stop"). The progression of the color code from Green
to Yellow to Red conveys progressively more restriction to the car driver. Unlike highway
signal aspects, rail signals are in spatial sequence for a given time (as oppose to temporal
sequence for a given location of a highway traffic light). The sequence of rail signal
aspects, GGG—GYG—YGY—YYY—YRY—RYR—RRR, becomes progressively more
restrictive as the train proceeds towards an occupied block (Figure 2.1). The obstruction
occupying a block automatically sets the signals behind it in a sequence (via a circuit logic
built into the track) that prevents the following train from entering the occupied block
(which has signal aspect RRR).

The meaning of a signal aspect to the driver is twofold. First, the signal may affect the
**effective** speed limit of the block. Effective speed limit is the minimum of the civil speed
limit of the block and the signal speed associated with the signal aspect of the block.
Therefore, the meaning of a signal is dependent on the particular block the train is in. For
example, if the signal is YYY (associated signal speed is 220 km/h) and the nominal speed
of the block is 250 km/h (or any speed above 220 km/h), the effective speed limit for the
block should be 220 km/h. The signal acts to restrict the civil speed limit which is higher
than the signal speed. The driver, upon perceiving such a signal, should start braking in
order to bring the train's speed to the next lower signal level when reaching the end of the
block (or at the entrance to the next block). If, on the other hand, the civil speed limit is
200 km/h and the signal is YYY, the effective speed limit is then 200 km/h. In this case,
the signal speed is higher than the civil speed limit and therefore has no restrictive effect on
the speed limit of the current block.

Second, from a signal aspect, the driver can infer the approximate distance to the upcoming
occupied block. That is, when a non-GGG aspect is seen, an RRR aspect must be some
blocks ahead. The number of blocks depends on the non-GGG aspect seen. For example,
when the signal aspect YYY is seen at the entrance to a block, it can be deduced that an
RRR signal aspect is 3 blocks ahead. Therefore, even when a signal has no restrictive effect on speed limit for a particular block, it still tells a driver how far an occupied block is ahead of him or her. Much like the traffic light on a highway, when a Yellow light is seen, one would expect the next level of light must be Red after a few seconds. The signaling system is designed or wired this way.

**Figure 2.1 The 6-Block 7-Aspect Block Signal System.** *Top:* Signal aspects displayed to protect this piece of road (of identical 2-km blocks). *Bottom:* Illustration of corresponding signal speeds following an occupied block. Assume that train A has stopped in block 1 (the number above the signal lights corresponds to the number of the block to the right), and a following train B is approaching signal 7. Signal 7 is GGG ("proceed"); therefore, train B will continue at its normal speed (assuming the civil speed limits for the shown blocks are 300 km/h) until it approaches signal 6, which will be GYG. Then the driver of train B will start braking in order to bring down the speed to 270 km/h at the end of block 6 or the entrance to block 5. Assume that the signals are spaced just braking distance apart, then train B should continue braking after crossing signal 5 in order to bring down the speed to the next signal level (YYY, 220 km/h) at the end of block 5 or the entrance to block 4. This process of braking continues until the train stops inside block 2—before running into the red light at the end of block 2.
2.3 A SYSTEM ANALYSIS OF DRIVING BEHAVIOR

2.3.1 Characteristics of Train Driving

A train's speed on a block signaling system is governed by stepwise speed limits and signals along a line, and can be manipulated by a controller via application of braking or propulsive force (also called traction force or tractive effort). From the outset of railway operations, observation of the speed limits and signals at all times is essential because of the potential risks involved: collisions between trains (rear-end or head-on), derailing at switches or curves due to excessive speed, or striking road vehicles at highway crossings. Therefore, the critical and primary task in the operation of a train is speed control under the constraints of speed limits and signals. This implies that if the train is approaching a speed reduction point, its speed should be controlled to below the new speed limit before, not after, the point of speed reduction.

Such a requirement in train speed control suggests that the control behavior of a train controller (be it human or machine) is fundamentally different from that of a conventional (proportional-integral-differential or PID, or optimal control) automatic controller. A conventional controller which operates on instantaneous error between current input (speed limit) and actual measured output (speed) has no way of taking into account actual values of its immediate future input, such as the next speed limit along the route for a train. Such a controller would not be able to operate the train without speed infraction.

Indeed, for high-speed train control, not only is the instantaneous speed error necessary, but also future inputs (i.e., upcoming speed limits, signals, or disturbances) are crucial for decision on current control. For a human driver, anticipation of these future inputs demands his/her looking ahead for potential signs that may affect a current control maneuver. The demand on the controller to anticipate future inputs and make a proper current control decision is exacerbated by the large inertia of the train and the high speed at which the train operates. The heavier the vehicle, the longer the time constants; the faster the vehicle, the longer the stopping distance of the vehicle, and the farther ahead the driver must look in order to achieve smooth and safe speed control [Sheridan 1966].
2.3.2 A Paradigm of Train Speed Control

Under human control, a train can be regarded as a semi-automatic system, where the driver functions as a controller between the input of the train and its output: he or she adjusts the level of control force in order to achieve the desired speed. Functionally, the human-machine relationship can be represented by the information flow diagram shown in Figure 2.2. Two major sources of input to the human are identified and depicted in this figure: the external information and the servo feedback information. Assuming a conventional line, the information content and corresponding functional significance are described below.

External Information. External information, or information from out-the-window view, refers to the items of relevant information, such as signs, signals, obstacles, and so on, that are to be detected, perceived or interpreted correctly and in a timely manner in order to form a target speed. Unlike an ordinary servomechanism, where system control compensates for instantaneous error by operating upon present or past values of error or both, the control of a train depends importantly, though not exclusively, on preview of what is ahead. This is because moving vehicles (including trains, cars, and planes) are target-oriented and consequently their output (i.e., the motion variables) should be adjusted in relation to a target output. The target output is formulated by observing the nature of the path ahead (signs, signals, speed limits, and so forth). This driving behavior holds mainly for vehicles in surface traffic and for airplanes during take-off and landing [Mashour 1974].

![Figure 2.2 Paradigm of Information Flow in Driver-Train Systems.](image)

\[X_{\text{target}}, V_{\text{target}}\]—position of train. \(V\)—speed of train. \(F\)—propulsive or braking force.
The meaning of "target" in the context of train driving may be explained as follows. On an open line, the speed limits and signals are basic commands that governs the train's output variable, the speed. The driver is expected to control the train such that before, rather than after, entering the next block, its speed should be under the speed limit of the new block. Therefore, the driver needs to know the distance to the point of and the amount of speed reduction in order to initiate braking in time to comply with the upcoming speed reduction. Getting such information requires the driver to look ahead—to preview, i.e., to continuously scan the field of view in search of future inputs in order to make current control decision. The future inputs, be they signals, speed limits, or dangerous situations, are transformed by the driver into a corresponding short-term or current desired speed—the target speed. During the course of driving, the driver, based on previewed information that is continuously changing due to the motion of the train, decides on a succession of target speeds. The target speed of the moment is the reference input for guiding the current application of control force.

In summary, the target speed has two important features.

1. It is not explicitly displayed to the driver. Instead, it is interpreted or inferred by the driver from the external information observed through actively looking ahead or scanning the field of view.

2. It has to be continuously updated because of (a) the appearance of new information (e.g., signs or signals) in the field of view as a result of the train's motion, and (b) the possible sudden appearance of dangerous situations.

**Feedback Information.** If the target speed is the short-term desired output, the control to achieve the target speed needs feedback about the current train speed. This information is usually provided inside the cab by a speedometer, which is the most significant feedback indicator for controlling the speed of the train. Another indicator related to speed control decision making is the traction or braking level currently applied to the system.

It should be pointed out that, besides the two sources of input to the train driver depicted in Figure 2.2, there are other sources of feedback on speed control. For example, the interactions that are associated with the speed might be used as cues in the adjustment of speed. Such information may be noise, vibration, or equilibratory factors that can be felt via tactile or kinesthetic channels.
2.4 EFFECTS OF HIGH-SPEED LOCOMOTION

Effects of “high speeds” on the human driver fall into two interacting categories: those on information processing of the visual system and those on decision making.

Effects of high-speed locomotion on the information processing of the human visual system are twofold. First, the capability of the human visual system for detection deteriorates as speed increases. Research findings and laboratory and field experiments [Mashour 1974] have shown that human limitations on detection and attention are not particularly critical in a natural environment when the motion is sufficiently slow for a more effective search by scanning the field of view. It is when the human is required to perform search tasks while under high-speed locomotion that his or her limitation in detection and attention can not always cope with the demands of the task and may even jeopardize safety. As such, driver identification of wayside signaling systems increases in difficulty as speed increases. In practice, a speed of 220 km/h is regarded as the maximum threshold for correct interpretation of a signal in poor weather conditions (for regular size of signals); with falling snow, the threshold is naturally lower [DOT/FRA 1991]. Second, as speed increases, other things being equal, the driver is exposed to increasing sensory load. The driver must scan the track and its vicinity more intensively to detect unexpected dangerous situations and signals. Under this condition, the probability of missing a signal increases.

Effects of "high speeds" on driver's decision making include those subjecting the driver to more demanding tasks, reduced allowable reaction time and increased memory load. First, because of the exacerbated severity of an accident at higher speed, drivers are expected to be absolutely attentive, vigilant, and make proper control decisions in case of dangerous situations. As a result, the demand on the driver for information processing increases per unit time as the train speed increases. Second, higher speed reduces the allowable response time for unexpected dangerous situations, such as sudden detection of an obstacle. Consequently, higher speed poses greater demands on the driver to anticipate or to be aware of the potential dangers and be able to make quick and appropriate control decisions. Third, high-speed locomotion increases the demand on the driver's memory. Train operation relies on a continuous retrieval of information of track characteristics, landmarks, Daily Operating Bulletin (which indicates temporary speed restrictions and the working area of track maintenance crews, among other things), operation rules, and so on. Such a memory retrieval process becomes increasingly intensive as the speed of the train increases.
2.5 IMPLICATIONS FOR DESIGN OF DECISION AIDS

The limitations of human information processing and effects of high-speed locomotion on the driver's visual functions suggest the following design requirements for signaling systems and decision aids:

1. At high speeds, traffic safety must no longer rely on correct interpretation of wayside signals by the driver. (In fact, a train running at a speed higher than 79 mph is required to have in-cab signals by the Federal Railroad Administration in the United States.)

2. To compensate for human deficiency in detection, signal displays should possess sufficient effect of sensory stimulation to attract the driver's attention.

3. Control decision aiding should address the issue of workload and help the driver make proper control decisions under both normal and emergency conditions.

2.6 CAB SIGNALS AND THE BASIC DISPLAY

The above considerations of decision aid design for high-speed train drivers has led to the replacement of wayside signals by cab signals in current practice. That is, the signal governing the current block of track is displayed inside the cab with the color aspects as used on the wayside, together with the display of the allowable (civil) speed of the block and a speedometer. With the cab signals, should a restriction change, the driver is immediately shown the new level of speed command from inside the cab, instead of searching for the signals at block boundaries (where external signals are traditionally located in the wayside signaling system).

A driver-cab interface including such cab signals was used in this research as a baseline for comparative study of the proposed aids. An implementation of such an interface, together with other onboard indicators necessary for speed control, is shown in Figure 2.3. This simulated cab environment, referred to as the basic display for convenience, contains the usual cab signals and indicators as described below.
Figure 2.3 The Basic Display. 1: Current speed 2: Civil speed limit of current block 3: Civil speed limit of next block 4: Signal of current block 5: Current kilometer post 6: Current block number 7: Grade of track at current location 8: Force indicator (traction or braking) 9: Distance to next station 10: Current time.
2. Design of Decision Aids

The speedometer, located in the center region of the screen, integrates current speed, speed limit of the current block, and speed limit of the next block. The rectangular shape of the speedometer was chosen specifically to provide a "common look" among the displays under comparative study. In fact, the rectangular shape of the speedometer was a natural fit with the proposed aids discussed in Sections 2.7-2.9.

To the upper right of the speedometer is the cab signal consisting of three colored lights. Each of the lights may be \textit{G}—green, \textit{Y}—yellow, or \textit{R}—red at certain times depending on the track condition ahead (e.g., being occupied at some distance away). The function of the signal aspects and their meaning to the driver has been described in Section 2.2.

The control interface between the driver (subject) and the train simulator was provided via a dual-use throttle that was programmed to be capable of applying both braking and traction, with each function allocated one half of the throttle throw. The throttle has a center notch to provide tactile feedback on its functional position (braking vs. traction).

The indicator corresponding to the dual-use throttle is a horizontal grid bar located under the frame of the central region in Figure 2.3. The center grid of this indicator corresponds to the center notch position of the throttle. Functionally, this position of the throttle is neutral; i.e., no braking or traction is applied. To the left of the center grid, braking is displayed; to the right, traction level. The throttle is capable of continuous force application (as compared to notched levels) and its indicator is displayed accordingly. The grid lines on the force indicator are provided as measures of force level at every 10\% of the maximum braking or traction.

Functions related to speed control are provided on the right side of the screen of the cab display simulation computer. Two functions are shown in Figure 2.3: the automatic train protection (ATP) system and the emergency stop (although other functions such as cruise control, automatic control, and programmed station-stopping are available in the simulator). The emergency stop can be activated manually either via a press on the keyboard (F12 key) or via a mouse-click on the emergency-stop indicator. The ATP system warns the driver (by blinking its triangular indicator) when the speed of the train is above the speed limit. It automatically activates the emergency stop when (1) the train is more than 15 km/h above the speed limit, or (2) the speed of the train is in the warning zone (within the 15 km/h overspeed tolerance) for more than 20 seconds. Emergency braking, whether activated manually or automatically, cannot be reset until the train has stopped.
2. Design of Decision Aids

To the lower left of the speedometer (outside the central region) is the door status indicator. The door is opened or closed by a click on the door display to toggle the door *open* (red) or *close* (gray) when the train is not moving. Conversely, the train cannot move unless the door has been closed.

The alert-system status display, located just under the door indicator, generates a blinking-yellow warning. The warning is activated by the alert system with a random period ranging from 40 to 80 seconds. Once the warning is active, the alert system expects an acknowledgment or response from the operator. The response could be either a press on the keyboard (*Esc*) or a throttle maneuver. If no response is received by the alert system in 10 seconds after the initiation of the warning, the alert status display changes to blinking red accompanied by beeps. If no response is received in another 10 seconds, emergency braking is automatically activated. Again, emergency braking cannot be reset until the train has come to a complete stop.

A call-up schedule display is provided at the lower left of the workstation screen. The schedule, which can be shown or hidden by a mouse-click on the *schedule* button, consists of arrival, departure, and station-stopping times for each station and the distances between stations on the journey.

On the right of the call-up schedule display are the incoming and outgoing message areas. The incoming messages from the dispatcher at the Central Traffic Control are displayed in the *CTC MSG:* area, with the most recent message at the bottom of the area. (Other messages are scrolled upward). The driver can type a message at the *MSG:* area and send it to the dispatcher with a mouse-click on the *send* button (at the far right of the *MSG:* area).

Other on-board subsystems are displayed on the right side of the workstation screen. Displays for subsystems, such as a side task or ride quality, can be rapidly prototyped using these display areas. The train dynamics are based on the longitudinal point-mass equations of motion (Appendix B). The train data used in the simulation is for a TGV Atlantique trainset [DOT/FRA 1991].

The limitations of the *basic display* can be readily observed in view of the effects of high speed on human performance discussed in Section 2.4. The cab signals are limited in their capability to satisfy the demand to preview farther when the speed gets higher because the previewed information in this display, i.e., the speed limit of the next block and signal of the current block, only provides a preview of no farther than the block length (usually 2 km). This limitation becomes most severe for highly dense traffic where shorter headway
requires a shorter block length. As the speed of the train increases, such short notice may not be sufficient for the driver to anticipate and respond in time. The long stopping distance at high speed demands a farther preview. In addition, the simple display of the cab signal as used in the wayside system may not have sufficient sensory-stimulation effect—one of the requirements for designing signaling systems discussed in Section 2.5. Further, if the cab signals in the basic display are regarded as an aid for the driver's visual or detection limitation, then the basic display does not provide the driver with any aiding on decision making.

2.7 PREVIEW AIDING AND THE PREVIEW DISPLAY

In view of the preview behavior of a vehicle driver and the visual limitations of the human driver, hard-pressed by high-speed locomotion, a natural question is: is it feasible to design an aid to compensate human visual limitations by enhancing the preview that is so crucial in train operation? Given modern measurement, communication and computer technologies, such aiding can be realized. As such, this research proposes an implementation of such preview aiding, referred to as the preview display, as shown in Figure 2.5. In addition to all indicators in the basic display, with an operator-adjustable (via keyboard) preview range from 0.1 to 20 km, the preview display presents the following preview information: kilometer posts, block boundaries, civil speed limits, signals, grades, stations, and switches. The respective indicators are described below.

Preview of kilometer posts—Vertical (white) lines across the preview range. Counted from the origin of a trip, the kilometer post numbers are marked at the lower ends of the posts in the display. The preview of kilometer posts provides a distance scale for the rest of the previewed information. The current location of the train is marked by a white-arrowed line aligned with the right of the speedometer.

Preview of block boundaries—Thick, short (yellow) vertical lines with the corresponding block numbers marked at their top right.

Preview of civil speed limits—for each block in the preview range, the civil speed limit is indicated by a horizontal (red) line segment. The height of the line corresponds to the civil speed limit of the block, with the speed scale being provided by the speedometer.

Preview of signals—for each block in the preview range, the signal is indicated by a set of three rectangular lights that functions the same way as in the basic display (Section 2.6). In
2. Design of Decision Aids

particular, the signal could be one of the 7 combinations associated with the 6-block 7-aspect signal system used in this study. With the notation of G—green, Y—yellow, and R—red, the 7 combinations are GGG, GYG, YGY, YYY, YRY, RYR, and RRR, progressing from "no restriction" (the train may go as high as the civil speed limit allows) to "stop" (must stop before this set of lights).

For each block, the height of the bottom of the three signal lights corresponds to the effective speed level, which is the lower of the civil speed limit and the signal speed of the block. For example, if the signal is GGG, the bottom of the signal is aligned at the current speed limit level; if the signal is RYR and the civil speed limit of the block is 250 km/h, the bottom of the signal is aligned at the 80 km/h level. (Note that the speedometer provides the speed scale.) Therefore, unlike the cab signal in the basic display whose location remains unchanged when the signal aspect changes, the previewed signals re-locate vertically depending on their signal levels.

Preview of grades—The side view of the track profile for the preview range, with the current location of the train as the horizontal reference.

Preview of stations—A station within the preview range is indicated with a house-like (yellow) icon with the station name marked beneath it.

Preview of switches—A switch within the preview range is marked by an "X" at the corresponding location on the track profile (the side view).

In addition to the above previewed information, the momentary full-service stopping distance (the red diamond) is also shown as a decision aid for the driver. Further, a trip-leg overview display is provided in the area under the lower left of the central preview region. It graphically indicates the current location of the train relative to the previous station and the next station. Furthermore, although not yet implemented, such a computer-based preview display has the flexibility of integrating other important variables such as weather conditions, locations of tunnels and bridges, and the Daily Operating Bulletin (DOB) that presents the DOB information along a profile of the track [Lamonde 1993].

Several advantages of preview aiding were expected. First, preview aiding would improve driver situation awareness because the signals displayed in multiple blocks would provide salient sensory stimulation and attract the driver’s attention. In case of a speed reduction set off by an obstruction ahead, changes in signal aspects of multiple blocks are simultaneously shown as opposed to only the current block in the basic display. The changes in signals are
reflected in the preview display not only by changes in signal color of the affected blocks but also by shifts in the location where these signals are displayed with respect to speed. It is the multiple block signals and their color changes, as well as the position shift in the preview display, that exert sensory stimulation, attracting the driver's attention and contributing to the driver's situation awareness.

Second, the preview aiding would reduce driver visual workload. There would be no or reduced need for the driver to intensively scan the fast moving field of view to search for signals or signs. The operator-adjustable range of the preview would allow the driver to control the amount of information presented to him or her, instead of being at the mercy of the fast flow of the visual field. Therefore, the preview display was expected to relieve the driver of visual overload and increase his or her signal detection capability.

Third, the previewed information on track geometry, switches, and so on would help to reduce driver mental and memory load. A principal learned skill that the drivers depend upon for speed control is "knowing the track", or anticipating the grades, speed limit profiles, etc., in order to (1) smoothly maintain the proper speed for each block, and (2) make smooth transitions to different speed limits at subsequent blocks. The speed control is continually and actively adjusted by the driver, even though the nominal speed is constant, because of track geometry (e.g., grade) and other disturbances. Preview of information such as track geometry, civil speed limit profiles, switches, and so on would reduce the driver's reliance on memory of track details and thus reduce the mental effort required.

Fourth, the quality of decision making on speed control was expected to improve. The minimum full-service stopping distance indicator serves to relieve driver mental workload and help decision making in case an obstruction appears in the preview range. Without this item, the driver would have to exercise his or her mental model of the train dynamics and estimate the braking distance in order to make a proper judgment as to the use of emergency braking. Correct decisions that avoid unnecessary use of emergency braking were expected to increase with this aiding. Without such aiding, the driver (to be safe) would frequently rely on emergency braking in case of an unexpected obstruction, possibly inducing unnecessary injury to passengers and damage to equipment. This preview display, however, is limited in its power to aid the driver for such decision making. Therefore a predictive aiding was proposed and is described in Section 2.8.
Figure 2.4 The *Preview Display*. 1: Current speed 2: Civil speed limit of current block 3: Previewed civil speed limits 4: Signal of current block 5: Previewed signals 6: Previewed track elevation profile 7: Grade of current location 8: Location of train 9: Block boundary and number 10: Kilometer post 11: Full-service stopping distance indicator 12: Station 13: Force indicator (traction and braking) 14: Trip-leg overview map.
2.8 PREDICTIVE AIDING AND THE PREDICTOR DISPLAY

Human operators have internal models of themselves and their environments [Kelley 1968]. They seem to plan their actions and predict responses through their internal models of the system and the environment. They form a desired goal by planning, and predict potential outcomes by incorporating the situation information into the model and extrapolating it into the future, however short it might be. For the case of a train driver, the planning is achieved by preview of the up-coming environment and formulation of a target speed of the moment. Prediction of the train's response to a control input is accomplished by the driver's estimation via an internal model of the train's dynamic responses to control. Control is normally exercised based on the difference between the desired output (the target speed for the train) and the predicted output.

During the operation of a high-speed train, the process of prediction of potential outcomes to guide the adjustment of control increases in intensity as speed increases. The fast changing environment (grades, curvature, gust winds, and so on) and the nonlinearity of the train dynamics make accurate prediction extremely difficult. The nonlinearity of the dynamics of a train increases the difficulty of anticipating its response. As a result, the driver's mental workload may increase and performance of speed control may deteriorate. Safety may therefore be in jeopardy in the train operation.

This research proposes two types of predictive aiding to relieve the driver's mental load and aid his or her control decision making. One type of predictive information answers the question *what would be the speed profile for the next period of time if the current force application were maintained*; the other type of predictive information answers the question *what would be the speed profile if the full-service braking or emergency braking were quickly applied now*. An implementation of these aiding profiles in the driver-cab environment interface, referred to as the *predictor display*, is shown in Figure 2.5. Both types of prediction can be obtained by integrating a fast-time dynamic model of the controlled system (i.e., the train) with the current state of the train as initial conditions [Sheridan and Ferrell 1974]. Figure 2.6 depicts the process of prediction of the speed profile for the next $\theta$ seconds assuming no further control action is applied to the train during this time span. The time span into the future for which the system response is predicted on a fast-time scale and displayed is called *prediction time span*. 

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Figure 2.5 The Predictor Display. 1: Current speed 2: Civil speed limit of current block 3: Previewed civil speed limits 4: Signal of current block 5: Previewed signals 6: Previewed track elevation profile 7: Grade of current location 8: Location of train 9: Block boundary and number 10: Kilometer post 11: Prediction of speed for next 20 seconds 12: Full-service braking curve 13: Emergency braking curve 14: Trip-leg overview map 15: Force indicator (traction and braking) 16: Station.
2. Design of Decision Aids

The prediction time span is a design variable associated with a predictor design. The choice of the prediction time span depends on the system time constants and on the computation capability. Larger system time constants imply that a longer prediction time span is possible with moderate computation speed. However, if the span is too long, real-time display of the predicted trace may not be possible due to computation limitations. A short prediction span, on the other hand, will not permit the operator to sufficiently anticipate the results of his or her control movements to keep the system stable or under control. Although the prediction time span in the predictor display is readily adjustable (with a command-line option in the train simulation system), a 20-second prediction was deemed to be sufficient and was set in the predictor display (Figure 2.5).

The principle of predictive aiding is therefore to use an external computer model to generate more accurate predictive information to help the humans build their own internal models and to improve the performance of manual operation. For nonlinear dynamic systems such as a train, the human operator cannot predict changes in output accurately and easily. He or she may have to wait until perceivable changes of the speed occur, and then correct the control application. This difficulty of prediction by the driver because of nonlinearity and slow dynamics increases the driver's mental workload. The slow dynamics feedback may lead to additional undesirable results, e.g., speed violation, derailment, or even collision. With the proposed predictive aiding, future tendency of output and instant prediction of the control outcome is explicitly displayed to the driver who is then able to take corrective actions much earlier.

Another advantage of the predictor display is that it explicitly indicates to the driver the dynamic limitations of the system via the full-service and emergency braking curves. These
prediction profiles not only relieve the driver's mental effort in estimating or extrapolating the curves during the process of control, but also provide a guideline or basis for strategic application of available control forces for energy-saving operation.

Predictor displays showing extrapolated future outcomes under the current control level have been investigated intensively in laboratory simulations [Wierwille 1964, Dey 1971, Johannsen et al. 1980, Hashimoto et al. 1986, Cheng 1991]. They have been found to reduce human workload and result in improved performance. Such predictor displays have been demonstrated to work well on systems having very-low-frequency reference inputs or disturbance inputs or nonlinearity [Kelley 1968, Cheng 1991]. Kuehn [1992] also reported improved train control performance with a display of a one-point prediction of future speed (as opposed to a profile of future speed).

2.8 ADVISORY AIDING AND THE ADVISOR DISPLAY

In addition to safety concerns addressed in the previous sections, the last in the proposed series of displays, with aiding level graded from less to more, offers additional aiding over the predictor display. This high-level aiding addresses the issue of optimal speed control by the driver—optimal in terms of energy consumption under the constraints of schedule, speed limits, passenger ride quality, and train capabilities.

It was proposed that an optimal speed profile, calculated from the origin station to the destination, can be obtained and used for the driver to follow in order to produce a minimum-energy run. Technically, it is now quite feasible to realize such advisory aiding such that, if the advisor is followed perfectly, the train would travel within prescribed speed limits, arrive on time, move smoothly, and, under these constraints, simultaneously minimize energy consumption. Automatic measurement of train position, speed, tractive effort, braking, and other variables have steadily improved, and advanced cab signal systems are becoming available. Modeling of train dynamic characteristics is more precise with the advent of new technologies. Computers are becoming faster, cheaper, and more reliable, which allows implementation of computationally demanding algorithms that were not possible earlier. Therefore, once the current location, time, and scheduled next-stop location are known, it is possible to obtain an optimal solution of the speed control for the whole trip that yields a minimum energy consumption.

The advisor display, shown in Figure 2.7, provides the human driver with the "optimal" speed profile, called the advisor, as a function of train position, that meets all the given
speed limits, gets the train to the next station on time, and minimizes energy consumption as well. Dynamic programming techniques were used to solve the highly constrained optimization problem (Appendix C). The advisor is integrated with the predictors and preview to help the driver make decisions about the type of or amount of braking force to use in the event of an obstacle or an unexpected change in signals. Under normal operation, if the human keeps precisely to such a profile, it is claimed that he or she would have a better speed-control performance than by mentally performing the various calculations required for reaching the optimal control decisions.

It should be noted that in practice it is unrealistic to expect a train to follow the optimal speed profile even if the driver follows the displayed “optimal” speed profile perfectly. A major reason is that the model used in calculating the optimal solution may not conform precisely to reality. The train moves as a net result of its own propulsive force or tractive effort and the external forces. In obtaining the optimal solution (Appendix C), however, only three major elements of resistance are modeled in the equations of motion of the train: (1) rolling resistance which includes the resistance to wheels rolling on the rail, friction in the axle bearings on the cars, and aerodynamic drag on the train body, (2) grade resistance, and (3) curvature friction. Therefore, the resistance force in the model does not represent that induced by, for example, instantaneous wind gusts. As a result, the optimal solution obtained for the whole trip may not remain optimal after a large disturbance that was not accounted for in the model. One way of remedying this situation is by updating the optimal solution for the remainder of the trip once the train has deviated from the optimal state. Using the deviation of the current speed from the optimal speed or the current time from the scheduled time or both as a cue, the driver may request the computer to update the optimal solution.

Owing to the relatively long computation time involved in obtaining an accurate optimal speed profile, this research is restricted to presenting an optimal profile for the whole trip without updates, and studies the behavior of the driver under such aiding. The author believes that the lack of dynamic updating of the optimal profile does not affect the finding on human use of such an advisory aiding because (1) it is relatively easy for the driver to follow the advisor because of the slow train dynamics and the presence of predictive aiding, and (2) even if updating is allowed, it would have been assumed that the updating is "fast enough" and the driver would not perceive the difference between old and new advisors.
Figure 2.7 The Advisor Display. The curve across the preview range and under the speed limit profile is the advisor.
2.9 SUMMARY

This chapter expounded the underlying rationale and considerations that support the proposal of the three levels of aiding for control of high-speed trains. First, a paradigm of human driving was developed and discussed. The concept of preview as applied to the train driving situation was defined and discussed. Effects of high speeds and their implication for design of decision aids in driver-cab interface were also discussed.

Three integrated displays corresponding to the three levels of aiding were described and discussed. These displays, referred to as the preview, the predictor and the advisor displays, are graduated in level of aiding from low to high with each higher level encompassing all information contained in the next lower level display.

The preview display contains not only the conventional cab signals and driver-cab environment interface information as shown in the basic display (simulating a conventional cab signals and interface), but also the preview information related to speed control and situation awareness. This display is expected to increase driver's capability in signal detection.

The predictor display provides the driver with three predicted speed profiles: the profile that the train would trace if the control level were held unchanged for the span of the prediction (20 seconds), and the profiles if the full-service braking or emergency braking is applied at the current moment. The predictor display is expected to reduce mental workload of the driver and improve quality of control decisions and therefore improve safety.

The advisor display, in addition to including all aids in the predictor display, shows an optimal speed profile acting as an advisor for the driver to follow in order to achieve minimum energy consumption. The advisory aiding (the optimal speed profile) was designed for improving operation efficiency and therefore was expected to reduce energy consumption as well as enhance safety.
CHAPTER THREE

EVALUATION OF PREVIEW, PREDICTIVE, AND ADVISORY AIDING

3.1 INTRODUCTION

Since each of the proposed displays provides more information to the driver than the basic display does, natural questions are then: Would the proposed displays improve the driver's situation awareness and thus increase safety as expected? or would the aiding provide too much information and overload the driver?

A preliminary human-in-the-loop experiment was conducted to investigate the preview aiding in view of the above concerns, since the preview is the foundation of the higher level aiding (i.e., predictive and advisory aiding). In particular, this preliminary investigation focused on comparing driver performance while using the preview display with that while using the basic display. The primary experimental question was how the preview display would affect operator workload and situation awareness. The results of the preliminary experiment strongly indicated that preview enhances safety by improving situation awareness, lowering workload, and reducing occurrences of speed violation. In spite of subjects' minimal experience, preview also showed promise of improving schedule adherence and station-stopping accuracy.

Backed by these encouraging results, the main human-in-the-loop experiment was conducted to investigate effects of preview, predictive and advisory aiding on human control of high-speed trains. In particular, this experiment focused on comparing system performance
Evaluation of Preview, Predictive, and Advisory Aiding

among three levels of aiding: (1) no aiding—with the basic display, (2) predictive aiding—with the predictor display, and (3) advisory aiding—with the advisor display. The predictive aiding was implemented as three predicted speed curves overlaid on the preview display. As the highest level of aiding under study, the advisory aiding took the form of an optimal speed profile and a projected delay in arrival time graphically overlaid on the predictor display. These aids and displays have been described in detail in Chapter 2.

Driver performance in safety and operation efficiency—the primary concerns when bringing any new information into the cab—was evaluated. Of particular interest in this experiment were (1) safety-related measures: situation awareness, appropriateness of decision making, workload, speed compliance, station-stopping accuracy, and (2) operation-efficiency-related measures: energy consumption, schedule adherence, and passenger ride quality.

Section 3.2 summarizes the preliminary experiment. The remainder of the chapter concentrates on the main experiment that fully investigated the proposed aids.

3.2 PRELIMINARY INVESTIGATION

3.2.1 Experimental Design

Test Design

A total of three test runs were performed by each subject, one under each of the following three test conditions: (1) with the basic display, (2) with the preview display, and (3) with the preview display in the beginning and a preview failure (reverting back to the basic display) approximately half-way through the test course. Conditions (1) and (2) allowed for comparative study of effects of aiding level—the independent variable of this experiment—on subject performance under normal conditions. Condition (3) allowed for evaluating subject's ability to recover after a loss of preview.

All three test runs were conducted on the same test course (144 km long consisting of three trip legs of roughly the same lengths and taking about 40 minutes to complete). The preview failure was designed to occur at a fixed location in the second trip leg. Situation awareness measurement was conducted by a temporary freeze technique [Endsley 1993], wherein the simulation is frozen at randomly selected times and subjects are queried about
states of the driving environment and the train system. In this experiment, measurements at
both random and fixed locations were conducted for all three test conditions with the fixed
location being three kilometers after the point of preview failure. Data collected from the
questionnaire about the states at the fixed location were of particular interest because they
shared the same driving environment. The locations of random freeze served as distractors
to counterbalance subjects' anticipation of a freeze; data from these freezes were collected
but not analyzed.

As shown in Table 3.1, the order of presentation of the three test runs was permutated
between subjects to counterbalance learning effects, and the sequence of temporary freezes
was designed to prevent anticipation of the fixed-location freeze. In particular, each subject
experienced two fixed-location freezes during the three tests: one was in the test with the
preview failure, the other was in one of the two other tests depending on the sequence in
which the three tests were presented to the subject. No two adjacent interruptions were at
the same location. The test with the preview failure always had the fixed-location freeze.

Table 3.1 Sequences of Tests and Temporary Freezes.

<table>
<thead>
<tr>
<th>Sequence #</th>
<th>Run #</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td>BASIC()random, fix</td>
</tr>
<tr>
<td>2</td>
<td>BASIC()fix, random</td>
</tr>
<tr>
<td>3</td>
<td>PREVIEW()random, fix</td>
</tr>
<tr>
<td>4</td>
<td>PREVIEW()fix, random</td>
</tr>
<tr>
<td>5</td>
<td>FAILURE()fix</td>
</tr>
<tr>
<td>6</td>
<td>FAILURE()fix</td>
</tr>
</tbody>
</table>

\text{BASIC} = \text{Test with the basic display},
\text{PREVIEW} = \text{Test with the preview display},
\text{FAILURE} = \text{Test beginning with the preview and with a preview failure in the middle},
\text{\(\)random} = \text{A freeze at a random location during the run \(\)},
\text{\(\)fix} = \text{A freeze at the fixed location during the run \(\)},
\text{\(\)random, fix} = \text{Two freezes with the random location before the fixed location},
\text{\(\)fix, random} = \text{Two freezes with the fixed location before the random location}.
3. Evaluation of Preview, Predictive, and Advisory Aiding

**Procedure**

**Training.** The experiment began with an explanation to the subject of the purpose of the study and an overview of the required tasks. A video [B&P 1992] about rail system operation and tasks of a locomotive engineer was shown to familiarize the subject with a realistic cab and wayside environment. The basic and preview displays were then demonstrated and explained. Next, under the teaching and supervision of an experimenter, the subject practiced on a short course (30 km) different from the test course (1) to become familiar with the displays, controls and use of the simulator, and (2) to understand the criteria for performance evaluation. Finally, the subject ran through a short trial section on the practice course for the experimenter to assess the subject’s capabilities and decide to either train the subject further or indicate readiness for the experimental test runs. The total training time was from 2.5 to 3.5 hours per subject.

**Testing.** Three test runs were then performed by the subject the following day. Next-day testing was chosen so that the training material was fresh in the subject’s memory. In fact, it was not practical to perform both training and testing on the same day because of the long hours (a total of about 7.5 hours for both training and testing).

To compensate for the insufficient time of training as compared with the amount of training a real locomotive engineer would experience (on the order of years), during the test runs, subjects were provided with a printed copy of operation rules, guides, in addition to track profile and geometry.

During each test run, the experimenter acted as the dispatcher, and communicated with the subject via typing on the keyboard. The communication was only needed before leaving and after arriving at a station, and when any failure occurred. Situation awareness questionnaires were conducted according to the sequence assigned to the subject from among the 6 possible sequences in Table 3.1.

A post-test workload questionnaire was conducted in order to obtain subjective ratings on time pressure, mental effort, and stress of the run just completed. For the run with the preview failure, the workload before and after the failure was rated separately. After the three test runs, an exit questionnaire was conducted in order to obtain the subjects’ ratings

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† This means of communication, simulating a typical radio system in actual train operation, provides advantages over voice implementation in terms of message recording and relative ease of analyzing communication performance. The disadvantage is the inherent delay in message generation.
3. Evaluation of Preview, Predictive, and Advisory Aiding

on the overall difficulty and their preference on the two displays. The experimental tests required 4 hours per subject to complete.

**Subjects**

Twelve undergraduate and graduate students from the Massachusetts Institute of Technology participated as paid volunteers. An incentive system was devised to help subjects prioritize and trade among aspects of performance and to encourage them to do their best. No selection criterion was used to screen or "filter" the subjects.

**3.2.2 Conclusions**

In spite of subjects' lack of training, the following conclusions were reached based on the results of this preliminary experiment (Appendix D).

1. The preview display was found to relieve subjects' workload, as measured by the Subjective Workload Assessment Technique, and was preferred by all subjects.

2. Situation awareness was observed to be improved with the preview because preview allowed the subjects to see ahead and prepare control actions earlier. This was evidenced by the relatively fewer occurrences of excessive overspeeding with the preview display than with the basic display. However, the situation awareness measured by a temporary freeze technique failed to reveal differences across displays, which was attributed to subjects' lack of training in general.

3. As a result of improved situation awareness, subjects committed fewer speed infractions, which shows the potential of preview in increasing safety.

4. Preview aiding seemed to help subjects keep on schedule and stop at stations more accurately than without the aiding. However, the absence of external visual cues in this experiment may have worsened the performance in station stopping without preview aiding, and therefore, positively biased the effect of preview on station-stopping accuracy.

5. No evidence was found to support the concern of subjects' being complacent after using the preview and not being able to resume control after a loss of preview.
3.3 EXPERIMENTAL DESIGN

3.3.1 Overview

In the main experiment, a total of nine test runs—three displays crossed with three types of test runs—were performed by each subject. Each type of test run, routine speed control, speed control with a secondary task, or speed control under an emergency scenario, was designed to investigate certain aspects of the wide categories of performance measures. The three displays were the basic, the predictor, and the advisor displays shown in Figures 2.2, 2.5, and 2.7, respectively.

Before testing, subjects underwent a rigorous training program, the design of which was motivated by results from the preliminary experiment. This program was designed to accomplish in a matter of hours, with a much simplified hypothetical driving task, the amount of training that real locomotive engineers would acquire in years for realistic train operations [National Transportation Safety Board 1992]. Two written exams and a road evaluation were conducted to qualify subjects to participate in the experimental tests. Failure to pass any of the exams or the road evaluation resulted in termination of the subject's participation in the experiment. The author conducted the training of all subjects throughout the main experiment.

Subjective workload was assessed via both an immediate-absolute method and a retrospective-relative method [Tsang and Vidulich 1994]. Subjects' ranking of and comments on the displays were obtained through a post-test questionnaire. Additional data was recorded by the simulation computer during the experimental runs.

3.3.2 Test Design: Routine Speed Control

Three types of test runs were designed to measure different aspects of the wide categories of system performance. One, referred to as routine speed control, simulated a hypothetical ideal situation where the driver's task was speed control only, and where signals were always clear throughout the trip. This test would allow evaluation of aiding effects on energy consumption, schedule adherence, station-stopping accuracy, ride quality, and speed compliance.

The test course, shown in Figure 3.1, was designed to be short and simple (30 km, straight and flat) out of two considerations: (1) to train a subject well in a reasonable time frame, i.e.,
in hours as opposed to months or years for real locomotive engineers, and (2) to reduce interactions between effects of displays and that of other nuance factors (e.g., grade), and thus simplify analysis. In each run, the train was initially positioned at the departing station, and was to be started according to a predefined schedule. The test course was scheduled to be completed in 11.5 minutes.

The outside view along the track was designed to be a night view with abstract scenery and landmarks to ensure quick learning and memorization of important "points of no return". There were two types of landmarks along the track: those located immediately before each block boundary (Figure 3.2 top), and those more salient ones located before critical points for optimal throttle manipulation (Figure 3.2 bottom). The former served to remind subjects of an upcoming new block, the latter to get subjects psychologically ready for a major control manipulation.

A head-up display, simulating the setting wherein a driver of Shinkansen (Japan's high-speed train, also known as the "bullet train") has a marker inside the cab to be lined up with a target at the station platform for accurate station stopping, was designed to provide cues for station stopping through the simulated out-the-window view. The head-up display (Figure 3.3) was projected onto the "windshield", i.e., the computer screen of out-the-window view, when the train was within the station range (800 meters before the station) for station stopping. A technique of using the landmarks for station stopping was developed before the experiment and fine tuned with the use of several subjects. Subjects were trained to learn this technique for station-stopping with the basic display. The technique can be summarized as follows.

To begin, the definitions of a station and a station point in the out-the-window view should be clarified. The station is a wire-frame building (purple and blue) with an entrance "door" at the front side and an exit "door" at the back side. Note that the "front" and "back" only differ from the perspective of the approaching train or driver; the wire-frame building is symmetric. The track goes straight through the building and the train can run through the building. The station point is a point inside the wire-frame station building, 30 meters in front of the exit of the station.

The head-up display (HUD) is shown on the "windshield" when the train is less than 800 meters away from a station point or within a station building. In particular, for approaching the destination station of the test course (Figure 3.1), the HUD was projected on to the screen when the train was 800 meters away from the station point, when the train's speed
should be controlled at 70 km/h. When entering the last block of the test course (80 km/h civil speed limit), the train's speed was to be reduced to 70 km/h (an experimental rule that required a safety margin of 10 km/h under the speed limit). Therefore, before approaching the station the train should be cruising at 70 km/h when the HUD is shown.

The out-the-window view in the last block showed pairs of tunnel lights (red) on either side of the "tunnel wall" (the last pair of the lights are shown in Figure 3.3.). The appearance of the HUD served to cue subjects to prepare for station stopping. As the train proceeded, pairs of red lights would pass by and cross the HUD frame. The instants when these lights moving past the HUD frame were used by the subjects (as they were trained) to determine the applications of braking level and the necessity of further adjustment of the braking level. For example, when the fourth set of lights (counted from inside the station toward the train) crossed the HUD frame, which was approximately 600 meters to the station point, the subjects were to apply full-service braking if the train was at 70 km/h (534 meters full-service stopping distance); when the third set of lights crossed the HUD frame, the subjects were to check if the speed of the train was approximately 60 km/h; and so on (Appendix E). Based on the observed speeds and the desired speeds at those locations, the subjects should adjust the throttle to make the train's speed match the desired speeds at the upcoming check points, until the perspective view of the exit-side wall of the station became the same size as the HUD, at which point the train should be stopped.

Note that because of the ceiling of braking capability, the rule described above was conservative in that each check point was associated with a slight undershoot. Note also that it is important to maintain the train's speed at 70 km/h because the rule was based on this initial speed. The subjects were expected to adjust the rule whenever their initial speed deviated from the desired 70 km/h: they had been taught how to do so before their experimental tests. A table of stopping distances at lower speeds was provided to the subjects during the training and testing (Appendix F).
3. Evaluation of Preview, Predictive, and Advisory Aiding

Figure 3.1 Test Course of the Main Experiment.
Figure 3.2 Landmarks in the Out-The-Window View. Top: Landmark (two blue towers) before a block boundary (block 7) or kilometer post 14. Bottom: Landmark (red overhead bridge) before a point of major throttle manipulation (start coasting).
Figure 3.3 Head-Up Display for Approaching Station. The largest rectangle in this "snapshot" is a head-up display (HUD) (yellow) that was projected on to the screen when the train was 800 meters away from the station point. The station is a wire-frame building (purple and blue) with an entrance "door" at the front side and an exit "door" at the back side. The station point is inside the wire-frame station building, 30 meters from the exit of the station. The perspective view of the station, smaller than the rectangular HUD at the moment shown, becomes larger as the train approaches the station. When perspective view of the whole back wall of the station becomes the same size as the HUD, the train is at the station point.
3.3.3 Test Design: Speed Control with Secondary Task

A test run of speed control with an additional secondary task was designed to measure the subject's spare visual capacity associated with the displays, and to provide a means to gauge, for each display, the sensitivity of workload to additional tasks. The secondary task was a simple first-order tracking task, displayed to the subject in the upper left corner of a display as illustrated in Figure 3.4. The state of the secondary system increases or decreases (visually moving up or down in the secondary task window) at a constant rate (0.3 unit/sec); reference input of the system changes discretely at a random cycle with a one-minute mean period. The subject's task was to keep the state of the secondary system as close as possible to the reference input by pressing the up- and down- arrow keys on the keyboard in his or her spare time.

The key phrase here is spare visual capacity—the assumption of performing the secondary task without sacrificing the performance of the primary speed control task. It is generally claimed that if a secondary task is not intrusive (as was found later), the better the secondary task performance (i.e., the smaller the tracking error), the lower the visual attention demanded by the primary task. Therefore, this test run allowed for an indirect evaluation of visual workload associated with the displays by objectively measuring subjects' spare visual capacity.
Figure 3.4 The Secondary Tracking Task (in the Predictor Display). The both-side-flushed line (dark colored) in the task window is the graphical display of the reference value (indicated above the line). The left-flushed line (light colored) is the graphical display of the current state or value of the tracking system with the value indicated at the right end of the line.
3.3.4 Test Design: Speed Control Under Emergency Scenario

A test run with an emergency scenario was designed to investigate the subject's situation awareness and quality of decision making. The emergency scenario simulated the situation when signals were suddenly changed due to either an obstruction or a defect of the track at some distance ahead. In particular, the scenario was designed to occur while the train was cruising at 240 km/h, illustrated in Figure 3.5. At the onset of the signal event the subject had 5 seconds to react (detect and perceive the signal, and apply full-service braking) before having to eventually resort to emergency braking to avoid running into the red lights. If his or her reaction time was long, a decision as to whether and when to activate emergency braking had to be made. A wrong decision could entail either unnecessary use of emergency braking or delayed initiation of necessary emergency braking. Potential outcomes of this test run were either a safe stop before the occupied block or a red-light overrun. These test runs allowed investigation of the effects of aiding on the subjects' times of reaction to the event and quality of their decision making, as well as sensitivity of subjects' workload to operational conditions with each display.

It should be noted that the emergency scenario was valid on the condition that the onboard automatic train protection (ATP) system had failed. The ATP system in the simulator was designed to activate the emergency braking whenever the speed of the train exceeds the current effective speed limit (the minimum of the civil speed limit and the signal speed of the block) by more than 15 km/h. For the designed scenario, at the onset of the event, the speed of the train was to be at 240 km/h—18 km/h above the signal speed (220 km/h, signal YYY). Without the assumption of an ATP system failure, emergency braking would have been activated immediately by the ATP system at the onset of the event without allowing for the subjects' intervention. Therefore, the emergency scenario implicitly included a failure in the ATP system. In fact, subjects were trained to accept that automation may fail at any time, and that they should not rely on the ATP system to perform control.
3. Evaluation of Preview, Predictive, and Advisory Aiding

Figure 3.5 Signal Event (at Block 6). Top: At the onset of the event. Bottom: After a delay in reaction of more than 5 seconds. The signal light notation is R—red, Y—yellow. A signal of YYY (220 km/h signal speed) implies that the next block should be more restrictive, the one further ahead should be even more, and the one three blocks ahead is a RRR signal. Therefore, when seeing the YYY signal at the entrance to block 6 while the train is at 240 km/h, the driver should apply full-service braking immediately in order to stop the train before the red lights without resorting to emergency braking. Note that the train should be kept under the signal speeds at the entrance to the corresponding blocks (YRY—160 km/h, RYR—80 km/h, RRR—0 km/h).
3.3.5 Within-Subject Experimental Design

As mentioned earlier, with the three displays and three run types, each subject performed nine runs on the test course. The sequencing of the nine test conditions was carefully designed, as shown in Table 3.2, to reduce anticipation of the signal event and counterbalance learning effects. This within-subject design achieved counterbalancing of learning effects and prevented predictability as to in which run the event might occur by satisfying the following design requirements: (1) For each display, the run with the emergency scenario can be the first or the second run. The very first of the nine runs to be conducted by a subject should not be that with an emergency scenario. (2) There should be no adjacent runs of the same type. (3) There should be no adjacent runs of the same display. (4) The number of subjects experiencing routine speed control without the secondary task before experiencing speed control with the secondary task should be equal to the number of subjects experiencing these runs in the reverse order.

Table 3.2 Sequences of Tests

<table>
<thead>
<tr>
<th>Sequence</th>
<th>Run #</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>R_B E_A S_P</td>
</tr>
<tr>
<td>2</td>
<td>R_P E_B S_A</td>
</tr>
<tr>
<td>3</td>
<td>R_A E_p S_B</td>
</tr>
<tr>
<td>4</td>
<td>S_B E_A R_P</td>
</tr>
<tr>
<td>5</td>
<td>S_P E_B R_A</td>
</tr>
<tr>
<td>6</td>
<td>S_A E_p R_B</td>
</tr>
</tbody>
</table>

R = Run of routine speed control
S = Run of routine speed control with the secondary task
E = Run with an emergency scenario
O_B = With the basic display
O_P = With the predictor display
O_A = With the advisor display
3. Evaluation of Preview, Predictive, and Advisory Aiding

### 3.3.6 Subjects

Twenty-four undergraduate and graduate students from the Massachusetts Institute of Technology participated in the main experiment. The subjects were pre-selected with the following two criteria: (1) a senior or junior with an engineering major, and (2) having car-driving experience or previous experience with the high-speed train simulator used in the experiment. Three of the subjects had previously participated in the preliminary experiment.

Of the 24 subjects, five were used to fine tune the training program and the experimental procedure, six failed to pass the evaluation during training, and 13 completed the experimental tests. Data from one of the thirteen who finished the tests, however, had to be discarded because of his apparent violation of a basic rule that led to incomplete performance data. Data of the remaining 12 subjects were analyzed and presented in this thesis. The individual data are presented in Appendix Q.

All subjects were paid for their participation. The pay rate varied with their performance during the test runs. Three cash prizes were awarded for top performers.

### 3.3.7 Procedure

#### 3.3.7.1 Training

**Overview**

To reduce training time, yet ensure sufficient training, the following five measures were taken in the experimental design. (1) The same simple and short test course and schedule were used for both training and testing. (2) The out-the-window view for this experiment was designed to be an abstract night view to eliminate distractions and to enhance easy recognition of landmarks. (3) Examinations and evaluations were conducted to filter out subjects who could not reach the required level in the designated training time. (4) Throughout the training and testing, subjects were provided with track and civil speed profiles (posted on the wall), a guide for optimal throttle manipulation (Appendix E), a copy of the stopping distance-speed profile (Appendix G), and a copy of the bonus system.

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† The rule: Except when the subject had to avoid and emergency situation, e.g., avoid a potential red-light overrun, no emergency braking should be initiated by the subject, especially not when approaching the station. The subject used the emergency braking unnecessarily for station stopping for two runs with the aided displays, while he performed satisfactorily in the training and seemed to understand the rule.
3. Evaluation of Preview, Predictive, and Advisory Aiding

(5) Immediate feedback was provided via both the author's coaching and a display of passenger ride quality, referred to as the *Jerkometer*, during each practice run, as well as performance feedback after the practice run.

The training consisted of three sessions and required a total of five and a half hours per subject to complete.

**Session 1: Teaching and Demonstrations**

The first session focused on teaching subjects basic concepts associated with operating a high-speed train and the simulator. After reading and signing a consent form (Appendix I), subjects watched a video [B&P 1992] and were then asked to read a short excerpt on *signal spacing* [General Railway Signal 1979] to familiarize them with train environment in real situations and a preliminary understanding of simple signaling systems. Next, the 6-block 7-aspect signal system used in the experiment and other related terms were interactively illustrated to them on the simulator. Then the features of the displays were explained and corresponding functions demonstrated. Desired operational performance and decision making behavior were also explained by demonstrations with examples. Finally, the subjects practiced, together with the instructor (the author), on drills of interpreting signals and correct decision making (Appendix J).

After the instruction and demonstration, a written test was conducted to examine each subject's grasp of the contents taught during the session (Appendix K). The objective of the test was to evaluate the subject's understanding of basic rail terminology, important characteristics of the train dynamics, functions of onboard safety systems, correct interpretation of signals, and desired control performance. A minimum grade of 90 percent was required to pass this examination. Although a group of two to three was preferred, most subjects were trained individually for this session because of difficulty in scheduling. This session took about two and a half hours per subject.

**Session 2: Hands-On Training**

The second session focused on subjects' learning the skills of operating the train on the test course with each display. The training allowed each subject to practice using the predictive aids (the three predictor curves) and the advisor, and reinforced subjects' understanding of all indicators in the displays, their memorization and recognition of important landmarks, speed limits and desired actions. Learning techniques of stopping at a station both with the
landmarks as cues—when using the basic display—and with the predictor aiding when available, was also an important objective of this training session.

Each subject practiced on the simulator a total of nine runs over the test course—three consecutive routine speed controls with each display. The sequence of the three consecutive runs was permuted between subjects to attenuate learning effects that might affect the evaluation of learning curves. During the training, the instructor (the author) acted as a well-experienced driving coach and accompanied the subject throughout the nine practice runs. All subjects were coached individually with the same objectives and contents of training.

Before starting the series of nine runs, the subject was allowed to try out the dual-use throttle (the mechanism for routine speed control), much like a person testing out the braking and accelerating behavior of an unfamiliar automobile. With a display of passenger ride quality, called the Jerkometer (Figure 3.6), the subject could soon learn the limiting movement of the throttle associated with an uncomfortable jerk. After each run, the subject’s trajectory was immediately overlaid with the optimal profile (the desired response) for comparison. This step of training proved to be a very effective feedback that explicitly showed the subject why his or her performance deviated from the desired measures and how to improve on the next run. A summary of performance in terms of total cost (energy consumption plus a weighted schedule deviation), speed compliance (in distance of overspeeding), schedule deviation, station-stop deviation and ride quality (in number of jerks), was then provided to the subject.

The hands-on training concluded with the subjects taking a written test (Appendix L). The test focused on evaluating the subject’s knowledge of (1) locations and associated actions for critical landmarks and major points of speed reductions along the track, (2) the train’s dynamic characteristics (approximate braking distance as function of speed), and, of course, (3) the use of the three displays. In addition, learning to adjust the preview range in appropriate times (via the keyboard keys) when using the aided displays was also a training objective. A minimum grade of 90 percent was required to pass.

In addition to the above written test, the subject’s qualification was also evaluated with his or her performance during the course of the practice runs. The evaluation was based on the subject’s performance in the third run with each display. Five performance criteria were assessed. (1) There should be no emergency stops. (2) The total overspeeding distance should not exceed 500 meters, the distance traveled at 180 km/h for 10 seconds. (3) A
station overshoot should not exceed 12 meters for the aided displays and 45 meters for the basic display; a station undershoot should not exceed 10 meters for the aided displays and 30 meters for the basic display. (4) There should be neither schedule delay of over 1 minute, nor early arrival of over 30 seconds. (5) The total number of uncomfortable jerks (greater than 0.06 g/s) for all three third runs should be no more than three.

This session of training took place at least six hours after the first session and lasted two and a half hours per subject (in fact, most subjects had this session on a different day from that of the first session). The subjects' learning curves recorded during the hands-on training session are presented in Appendix M.

Session 3: Pre-Test Training

Pre-test training took place the day after the hands-on training and immediately before the experimental tests. This session focused on training subjects to perform the secondary task while operating the train. Emphasis was given on the subjects' understanding of the task's relatively lower importance to the primary speed control task. This point was further driven home by explaining how his or her performance would be evaluated with a possible bonus awarded in the runs with the secondary task. The bonus system was designed to enforce the point of "secondary" (Appendix H).

Then the subject practiced decision making in the event of an unexpected change in signal (the speed and the location at the onset of the practice signal event are different from those in the experimental tests). The correct decision-making process was demonstrated and explained. Desired outcomes of decision making and corresponding bonuses were elucidated. Subjects were given opportunities to practice with all displays until they expressed readiness. Most subjects requested more practice with the basic display than with the aided displays (3 to 4 trials vs. 1 to 2). The pre-test training took approximately half an hour per subject.
Figure 3.6 Display of Passenger Ride Quality—the Jerkometer. The Jerkometer shows the rate of change of acceleration of the train smoothed in 0.2-second timer interval. A jerk within the tolerance (0.06 g/sec) was shown in the center (blue) wedge, a jerk larger than the tolerance would be shown in the outer (red) wedges. In order to simulate the effect of being harder for a person to rebound after a larger jerk, the jerk pointer will be "stuck" at a level for a time that is proportional to the level of jerk.
3.3.7.2 Testing

Immediately after the pre-test training, subjects executed the nine test runs in a sequence randomly assigned to him or her among the set of sequences carefully designed to counterbalance learning effects between subjects (Table 3.2). No Jerkometer was present during the testing, with the assumption that subjects, through the training, had learned the skill of driving with good ride quality. To avoid any anticipation that may affect performance, subjects were not told the total number of test runs. A questionnaire for subjective assessment of workload was conducted immediately after each run (Appendix N). An exit-questionnaire (Appendix O) was also conducted to obtain subjects' relative rating of overall workload associated with the displays as well as their comments and rankings of the displays, retrospectively. The experimental tests took approximately two hours per subject to complete.

3.3.8 Experimental Setting

Two Silicon Graphics workstations were placed side by side with the one on the right showing the out-the-window view and the one on the left showing the cab displays. Besides the two workstations used by the subject, a third workstation was used by the instructor to synchronize the simulation modules and monitor subjects' progress with the test runs—in order to conduct post-test questionnaires with minimum interference. All workstations communicated by a local area network. A description of the experimental facility is in Appendix A.

A realistic dual-use throttle provided both braking and traction capability: half of the throttle throw was for braking and half for traction, with a notch in the middle. In addition to the throttle, some keyboard keys and the computer mouse were used as speed control mechanisms and as controls for other tasks such as activating emergency braking, acknowledging the alert system, or changing the preview range.
3.4 RESULTS AND DISCUSSION

3.4.1 Notation of Data Presentation

Box-and-whisker plot [Tukey 1977] combined with scattered data plot† (Figure 3.7) is used to graphically present the data distribution. The top and the bottom of the box correspond to the 75th and the 25th percentile of the data. The center line inside the box is at the 50th percentile or the median of the data. The horizontal lines above and below the box, extended to by the dashed lines from the 75th and the 25th percentile, respectively, correspond to the maximum and the minimum of the data.

![Box-Scatter Plot For Graphical Data Presentation](image)

Figure 3.7 Box-Scatter Plot For Graphical Data Presentation

† Drawn with a Matlab® function written by Nicholas J. Patrick of the Human-Machine System Laboratory at the Massachusetts Institute of Technology.
3.4.2 Speed Compliance

During the runs of routine speed control, over-speed distance (or distance traveled when the train was above the current speed limit) was recorded as a measure of speed compliance. No subject committed a speed violation in any run with any display. This result indicates either (1) that subjects were well trained and therefore any biases potentially induced by subjects' lack of training were effectively reduced, if not eliminated; therefore, more confidence can be placed on the data obtained in testing, or (2) that the short test course (30 km) and the relatively small number of subjects (12) may not be enough to show effects of these aids on speed compliance, at least not from this particular measure. The result conforms with the practical expectation for a real locomotive engineer. In practice, it is unlikely that a well-trained driver (familiar with the dynamic behavior of the train and physical characteristics of the route) would commit a speed violation over a 30-km run.

For the runs with the secondary task, however, two subjects had incidents of speed infraction: one with the basic display for 515 meters in two incidents, the other with the predictor display for 33 meters. However, the automatic train protection (ATP) system was not activated because the former violations were 8 km/h above the speed limit (160 km/h) for 5 seconds and 14 km/h above the speed limit (80 km/h) for 10 seconds, the latter 1 km/h above the speed limit (80 km/h) for 2 seconds. These violations, in comparison with no violations for runs involving routine speed control only, hint that the secondary task may not have simply occupied the subject's visual spare attention, but competed with primary speed control for the subject's attention. Nevertheless, the effect of the secondary task on performance measures of speed control was not found to be significant (Section 3.4.9).

3.4.3 Time of Reaction to Signal Event

Time of reaction to the unexpected signal event in the runs with the emergency scenario was recorded to evaluate situation awareness. This reaction time is the span from the moment of signal occurrence to the moment when the throttle was at neutral position—assuming the subject was in the process of applying braking. This assumption was based on the fact that all events were designed to occur while the train, as shown in Figure 3.8, was cruising at 240 km/h which required 34% of full traction to maintain. It was found that the reaction time with either the predictor or the advisor display (\( \bar{X} = 1.4 \) seconds) was significantly shorter than that with the basic display (\( \bar{X} = 8.6 \) seconds) \( (p \leq 0.01, \text{Scheffé's test}) \). In addition, a much wider dispersion of the reaction times with the basic display was
observed than with the predictor and advisor displays. It could take a subject up to 31.1 seconds to react to the event as compared to the 3.2-second maximum reaction time with the predictor and advisor displays. Two samples of contrasting responses to the event are shown in Figures 3.9 and 3.10.

![Time of Reaction To Signal Event](image)

**Figure 3.8 Times of Reaction to Signal Events.**

The results strongly support the hypothesis that preview clearly presents the signal to the driver, attracts the driver's attention, leads to quick reaction, and therefore improves situation awareness. With improved situation awareness, safety and operational efficiency consequently increase, which is also demonstrated with a model simulation study in Chapter 5. The significant difference in reaction time between the basic and the aided displays may be explained by the following.

1. The change in the pattern of stimulation at the onset of a signal event was more prominent with the aided displays than with the basic display. With the basic display, the signal of only the current block was displayed inside the cab, whereas with the aided display, signals of multiple blocks were presented. At the onset of a signal event, changes in signals of multiple blocks, both in colors and in their display position, would surely attract more attention than that of a single block.
2. More head-down time was involved with the aided displays than with the basic display. With the basic display, subjects were trained and observed to rely mostly on the outside view for visual cues on optimal throttle manipulations since no other cues were as easily recognizable. More use of outside view resulted in less time to attend to the cab signal. The cab signal has the advantage of being instantaneous, whereas the physical signals at the wayside cannot be perceived when the signal sign is out of the driver's visual range.

In contrast, the two aided displays provided more cues for optimal throttle manipulation and hence reduced the subjects' reliance on outside landmarks as cues. In fact, during training, subjects were observed to look at the outside view only occasionally with the predictor display as opposed to frequently with the basic display. The previewed block markers and kilometer posts, for example, were used in conjunction with the landmarks shown in the out-the-window view. With the advisor display, whereby subjects were to follow the explicit guide of the optimal speed curve, the outside landmarks were not needed at all and were therefore rarely observed. The intensity with which subjects scanned the fast flowing field of view for landmarks was therefore greatly reduced by the presence of the preview aiding and the advisory aiding.
Figure 3.9 Sample Response to Signal Event With the Basic Display (Subject 4). It took about 16 seconds for this subject to react to the event. Further, he failed to apply emergency braking in time to avoid a red-light overrun. As a result, the train overran the red lights with a speed of 70 km/h.
3. Evaluation of Preview, Predictive, and Advisory Aiding

Subject perceived the signal change and applied full-service braking quickly (0.65 sec reaction time). He avoided a potential read-light overrun using only full-service braking, without having to resort to emergency braking.

Figure 3.10 Sample Response to Signal Event With the Predictor Display (Subject 11). Subject perceived the signal change and applied full-service braking quickly (0.65 sec reaction time). He avoided a potential read-light overrun using only full-service braking, without having to resort to emergency braking.
3.4.4 Decision Making in the Case of Emergency Signal Events

The most desirable response to emergency signal events was to engage full-service braking as quickly as possible (in less than 5 seconds) and stop the train before entering the occupied block. If the reaction was late (more than 5 seconds), emergency braking had to be applied at an appropriate time to avoid a potential red-light overrun. Too early application of emergency braking would result in potentially more serious passenger injuries and heavier equipment damage. Since the nature of the obstruction was unknown (subjects were instructed so), early application of emergency braking may not be necessary after all (e.g., if the obstruction turned out to be a fast moving train, which might lead to restoration of a normal signal level to the following train a few seconds after triggering the emergency event). On the other hand, too late an application of emergency braking would, of course, prevent avoidance of a red-light overrun (implying a collision) if the obstruction turned out to be a motionless object or defects in the track.

The outcomes under the emergency signal events, summarized in Table 3.3, strongly indicate that the predictor and advisor displays improved subjects' decision making under the emergency condition. First, no red-light overrun was committed with the aided displays, as compared to two such incidents (16.7%) with the basic display. This shows that the predictive aiding helped subjects to reduce chances of misjudgment as to the right moment to apply emergency braking. Apparently, the two subjects who committed red-light overrun misjudged the situations and initiated the emergency braking too late.

<table>
<thead>
<tr>
<th>Final State</th>
<th>Final Control</th>
<th>Display</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Basic</td>
</tr>
<tr>
<td>Red-Light Overrun</td>
<td>Emergency Braking</td>
<td>2/12</td>
</tr>
<tr>
<td></td>
<td>Full-Service Braking</td>
<td>0</td>
</tr>
<tr>
<td>Safe Stop</td>
<td>Emergency Braking</td>
<td>6/12</td>
</tr>
<tr>
<td></td>
<td>Full-Service Braking</td>
<td>4/12</td>
</tr>
</tbody>
</table>

Second, with the aided displays, subjects quickly responded to 96% (23 out of 24) occurrences of the event, and safely stopped the train before the occupied block, compared
to only 33% (4 out of 12) with the basic display. In other words, with the aided displays only 4% (1 out of 24) of occurrences involved late responses and called for emergency braking, as compared to 67% (8 out of 12) with the basic display.

Further, the speed at which the emergency braking was activated with the aided display ($\bar{X} = 19$ km/h) was much lower than that with the basic display ($\bar{X} = 108$ km/h, range of 40 to 183), as shown in Table 3.4. Because the emergency braking curve for the aided displays explicitly indicates the "last moment" or "point of no return", the speed at which the emergency braking should be applied could be easily discerned by subjects with the aided displays. In comparison, with no aiding, subjects were confronted with estimating the "critical moment" by themselves based on experience or by using the printed copy of speed-braking distance curves as provided (Appendix G).

<table>
<thead>
<tr>
<th>Moment</th>
<th>Display</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Basic</td>
</tr>
<tr>
<td></td>
<td>$N$</td>
</tr>
<tr>
<td>Activation of Emergency Braking</td>
<td>8</td>
</tr>
<tr>
<td>Overrun of Red Lights</td>
<td>2</td>
</tr>
</tbody>
</table>

### 3.4.5 Total Cost

The total cost of a trip is the sum of the total energy consumption (or the work done to move the train from the origin station to the actual stop point of the destination station) and a weighted schedule deviation. The weight on schedule deviation was such that the minimum-cost solution for the trip was the minimum-energy trip, i.e., the optimal solution was such that the train arrives exactly on time. It should be noted that energy consumption during a trip by a subject could not be fairly compared with the optimal energy consumption without considering the cost of schedule deviation; the subject could spend considerably longer time than that scheduled and expend much less energy than the optimal consumption which was obtained under the schedule constraint.

Subjects were trained to operate the train by following a written guideline on "optimal throttle manipulation" when the advisory aiding display was not present. The guideline was derived from the optimal control solution—the foundation of the advisory aiding. When the advisory aiding display was available, however, subjects were advised to follow
the advisor (the optimal speed profile) as closely as possible. The design of the advisory aiding for energy efficiency is strongly supported by the finding shown in Figure 3.11. The results show that the mean total cost with the advisor display ($\bar{X} = 10.3\%$ over the optimal) was significantly less than that with the basic display ($\bar{X} = 24.4\%$ over the optimal) ($p < 0.015$), as found through a repeated measures ANOVA ($F(2, 22) = 4.62, \alpha = 0.05$) followed by Scheffé's test. In addition, the box plots of Figure 3.11 reveal much smaller performance dispersion with the advisor display (ranging from 2.7\% to 16.8\% over the optimal) than with the basic display (ranging 7.5\% to 59.5\% over the optimal). Even the highest consumption with the advisor display (16\% over optimal) was lower than the 50th percentile of the consumption (18\% over optimal) with the basic display.

![Figure 3.11 Energy Consumption in Routine Speed Control.](image)

Performance in energy consumption with the predictor display seems to lay between that for the basic and advisor displays: higher mean value ($\bar{X} = 17.7\%$) than that of the advisor ($\bar{X} = 10.3\%$), but lower dispersion than that of the basic. Although no significant difference was found between the predictor and the advisor or between the basic and the predictor displays, the trend of the predictor having smaller dispersion than the basic was clear. This trend implies that, with the predictor display, it was easier for subjects to reproduce the optimal control. This may be explained by the additional cues presented by the preview and predictor aiding in the predictor display. It was this aiding that helped subjects be aware of critical points for optimal throttle manipulation.
With the basic display, however, subjects tended to deviate from the optimal trajectory more than with the predictor display. Excess application of full-service braking was especially observed for the track segment from kilometer post 23.2 (KP23.2) to kilometer post 28 (KP28). An example is shown in Figure 3.12.

Two possible explanations can be offered. First, subjects were uncertain whether the applied braking was sufficient during the track segment from kilometer post 23.2 (KP23.2) to kilometer post 28 (KP28). According to the optimal control (Figure 3.12), 88% of full-service braking was needed to bring the speed down to 70 km/h at the entrance to KP28. The location and speed at which this 88% full-service braking should be applied, however, was critical as to whether this amount of braking was enough or too much. With the basic display, large uncertainty was involved with determining the right moment to apply the optimal amount of braking (88% full-service braking). In addition, subjects were also uncertain whether the 88% of braking would lead to the needed speed reduction along this segment (from KP23.2 to KP28). As a result, more braking was applied to ensure safety.

Second, subjects were generally conservative about safety. With the basic display, continuous estimation was needed to ensure that the applied braking was enough to accomplish the speed reduction in the segment from KP23.2 to KP28. Subjects' estimation was usually conservative (to be safe) since it was relatively easy to violate the speed limit if insufficient braking was applied. Recall that overspeeding for more than 15 km/h would result in automatic application of emergency braking, which cannot be reset until after reaching a full stop. In addition, all subjects were trained to consider safety first and energy saving second. With the predictor display, however, more visual cues were available to assure subjects of the moment when the optimal braking was to be applied. The predicted speed profile and the full-service braking curve could help subjects avoid unnecessary use of full-service braking.

In summary, the uncertainty about the state of the train when an optimal manipulation was required, along with demand for safety prompted subjects to use full-service braking more with the basic display, resulting in more energy consumption than with the predictor display. While the predictor display allowed considerably lower energy consumption than the basic display, energy consumption with the predictor display was significantly higher than that with the advisor. After all, there are limitations on reproducing an optimal profile closely without its presence as a guide like the advisor.
Figure 3.12  The Optimal Control And a Typical Response By a Subject With the Basic Display. To be safe, this subject applied full-service braking (between KP23.2 and KP27.6) instead of 88% full-service braking as required in the optimal control, which induced more energy consumption.
3.4.6 Station-Stopping Accuracy

Station-stopping accuracy was evaluated with the absolute difference between the actual stopping point (the point where the train stopped under manual control) and the station. The results, shown in Figure 3.13, strongly support the hypothesis that the predictive aiding improves station-stopping accuracy. In particular, the aided displays reduced the mean station-stop deviation from 12.7 m with the basic display to under 1 meter with either of the aided displays (0.5 m with the predictor excluding the outlier explained later in this section, 0.8 m with the advisor display).

![Station-Stopping Accuracy (Routine Speed Control)](image)

Figure 3.13 Station-Stopping Accuracy.

The improvement can be attributed to the aiding provided by the full-service braking curve in the predictor and advisor displays. Generally, the subjects' technique of station-stopping with the aided displays was to align the tip of the full-service braking curve (which tells the momentary stopping distance) with the station point (shown explicitly by a trapezoid icon), using small adjustments of the braking near the full-service level. By increasing the display resolution via reducing the preview range (adjustable through keyboard keys), this process of throttle adjustment was easy and the adjustments could be both smooth and accurate. Once an accurate alignment was attained, the braking was maintained at full-service level until the train stopped, or to be exact, until the moment just before the train stopped when the braking should be reduced to under 30% full-service level to avoid a
moment of stop. Therefore, the full-service braking curve in the aided displays was a critical aid in attaining accurate station-stopping.

With the basic display, however, the technique of station-stopping was quite different. In the process of station stopping, subjects relied on a series of cues in the out-the-window view, along with the numerical display of the distance to the next station and their experience or memory of stopping distance-speed relations at the lower speed range. Before approaching the station, the speed of the train was to be maintained at the cruising speed of the last block of the trip (i.e., at about 70 km/h). When the train was 800 meters from the station, the head-up display (Figure 3.3) was projected onto the screen of the out-the-window view. By inspecting the speeds of the train at a series of critical moments (when tunnel lights crossed the head-up display frame), subjects could estimate the amount of potential overshoot or undershoot and thus adjust the braking accordingly. To stop accurately, subjects usually needed to maneuver the throttle in several (sometimes very large) swings depending on how accurately the subject estimated the crucial moment for applying the initial braking. If the application of initial braking was late, a large overshoot was unavoidable due to the ceiling of braking capability of the train. On the other hand, if too early, a relatively large time delay would be incurred. Under this condition, subjects tended to swing the throttle to traction to keep up the speed. Such corrections, however, were quite often overdone and resulted in overshoots as well as a relatively jerky ride for the passengers. Therefore, it was difficult to stop the train accurately with the basic display as compared with the aided displays. (This difficulty with the basic display in approaching the station implies that more training may be needed with the basic display than with the aided displays to reach the same level of station-stopping accuracy.)

The performance improvement in station-stopping accuracy is evident in Figure 3.13. However, the repeated-measures ANOVA just failed to reveal significance \((F(2, 22) = 2.294, p = 0.103)\) because the data distribution severely violates one of the assumptions associated with the analysis of variance: that the populations all have the same variance. A nonparametric statistical test, Cochran \(Q\) test [Siegel and Castellan 1988], was then applied on the station deviation data after being converted to two categories: 1—if the deviation is less than 2 meters, or 0—otherwise. This test disclosed that the effect of displays on station stopping accuracy was indeed significant \((Q = 18.18, df = 2, p < 0.001)\).

It should also be pointed out that the large deviation with the predictor display in Figure 3.13 (about 70 meters overshoot) was due to the subject's anticipation of the last test run. Guessing that the run was the last of the session, the subject explained that he "relaxed at
the end." At the moment when the initial application of full-service braking was due before the station, he inadvertently pushed the throttle to full traction. Of course, the result was a large overshoot, even though he quickly realized and corrected his manipulation error.

### 3.4.7 Schedule Adherence

Schedule adherence was evaluated with schedule deviation, which is the absolute difference between the scheduled arrival time and the actual arrival time. The results, shown in Figure 3.14, confirm the expectation that the aided displays would improve on-time performance. The aiding was found to have differential effect on subjects' schedule adherence ($F_{(2, 22)} = 4.143, p = 0.02$). Even for such a short test course (11.5 minutes scheduled), there was significantly shorter schedule deviation with the advisor display ($\bar{X} = 3.8$ s) than that with the basic display ($\bar{X} = 11.1$ s) (Scheffé's test, $p = 0.03$). Further, the small dispersion of the deviation with the advisor display shows that subjects consistently maintained schedule very well with the advisory aiding. In addition, strong trend of reduction in schedule deviation with the basic display ($\bar{X} = 11.1$ s) to that with the predictor display ($\bar{X} = 5.4$ s) was also observed (Scheffé's test, $p = 0.1$).

Two causes of schedule deviation with the basic display can be identified: (1) the train's running at lower than optimal speeds for the segment from KP23.2 to KP28 (Figure 3.12) due to the subjects' use of more braking than the optimal amount (discussed in Section 3.4.6), and (2) early braking when approaching the station. Being aware of the cost of overshoot (higher than that of undershoot), subjects tended to brake early for the station in order to avoid overshoot. As a result, the train was run at much lower speeds than optimal.

With the aided displays, however, the two sources of delay did not exist. Subjects could apply an appropriate amount of braking with the aid of the full-service braking curve and the predicted speed profile. Further, with the same aids, subjects could approach the station with the assurance of accurate stopping without excessive adjustments of the throttle, which made on-time, smooth arrival possible.
3.4.8 Ride Quality

Passenger ride quality, reflecting the driver's train-handling skill, was evaluated using the number of jerks incurred by subjects' sudden throttle maneuvers. Mathematically, jerk is the rate of change of acceleration of a moving object. In this experiment, however, a jerk was recorded only if the rate of change of acceleration of the train smoothed over a duration (0.2 second) was larger than a threshold level. The jerk threshold level was set to 0.06 g/s—approximately one third of the comfortable value (0.21 g/s) for standing passengers [Morlock 1978]—both for the Jerkometer display and for the evaluation of ride quality.

A trend of more jerks with higher level displays can be observed from Table 3.5. For the runs of routine speed control, there was a total of two jerks with the advisor display, one with the predictor, and none with the basic. Although the differences in number of jerks across displays was found to be insignificant by the nonparametric Cochran $Q$ test ($Q = 2$, $df = 2$, $p = 0.42$), the trend of increased number of jerks with increasing aiding was evident. This observation is further confirmed by the trend of the total number of jerks for the runs with the secondary task, as shown in Figure 3.15 (Section 3.4.9). The Cochran $Q$ test was also performed on jerks, combining, for each display, those of routine speed
control and speed control with the secondary task. Again, no differential effect of displays on ride quality was found ($Q = 2.25, df = 2, p = 0.47$).

<table>
<thead>
<tr>
<th>Run Type</th>
<th>Display</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Basic</td>
<td>Predictor</td>
<td>Advisor</td>
</tr>
<tr>
<td>Routine Speed Control Only</td>
<td>0</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Speed Control With Secondary Task</td>
<td>2</td>
<td>4</td>
<td>3</td>
</tr>
</tbody>
</table>

### 3.4.9 Spare Visual Capacity

Spare visual capacity associated with each display was measured with the secondary task described in Section 3.3.3. Better performance in the secondary task implies less visual load associated with the display in use. Performance on the secondary task was measured by the root-mean-squared (RMS) error over every half-kilometer of the test course (with an error sampling rate of 5 Hz).

To address the issue of possible intrusion on the primary task by the secondary task—a common concern about the method of secondary task loading for measuring anything about the primary task—an analysis was conducted to investigate the possible intrusiveness of the secondary tracking task used in this experiment. Paired t-tests were conducted on measures of interests (Figure 3.15) between runs of routine speed control and runs with the secondary task for each display. No significance was found for any of the measures with any display ($\alpha = 0.05$). Therefore, there was not sufficient evidence to suspect the intrusiveness of the secondary task designed for this experiment.

Important results on spare visual capacity were found by analyzing the RMS error profiles of individual subjects, an example of which is shown in Figure 3.16. Complete presentation of these error profiles are included in Appendix Q.

First, 75% of the subjects (9 out of the 12) committed their largest tracking error, as shown in Table 3.6, with either the predictor or the advisor display, while only 25% (3 out of the 12) did so with the basic display. Although this difference was not found to be significant ($p = 0.063$) by the Friedman two-way analysis of variance by ranks [Siegel and Castellan 1988], the trend is strong. This suggests that the basic display allowed subjects to have more spare attention, or more head-up time, for tasks other than speed control. The aided
displays, however, induced more head-down time and therefore may have restricted subjects' attention to non-speed-control tasks. Though the increased head-down time with the aided displays was a positive factor in signal detection and fast reaction to unexpected events (discussed in Section 3.4.3), this finding implies that this advantage may come at a cost of attention to tasks other than speed control.

Table 3.6 Rank Order of Maximum Tracking Errors
(by Display and Subject)

<table>
<thead>
<tr>
<th>Subject</th>
<th>Display</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Basic</td>
</tr>
<tr>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>5</td>
<td>1</td>
</tr>
<tr>
<td>6</td>
<td>3</td>
</tr>
<tr>
<td>7</td>
<td>2</td>
</tr>
<tr>
<td>8</td>
<td>2</td>
</tr>
<tr>
<td>9</td>
<td>3</td>
</tr>
<tr>
<td>10</td>
<td>1</td>
</tr>
<tr>
<td>11</td>
<td>2</td>
</tr>
<tr>
<td>12</td>
<td>3</td>
</tr>
</tbody>
</table>

Second, as expected, all subjects had increased average tracking error when approaching the station (the last kilometer to the station) as compared to their tracking performance enroute with any display, as shown in Table 3.7. The amount of increment was found to be significant \((p < 0.02)\) by a paired \(t\)-test on the mean errors for the last kilometer versus those enroute (the first 29 kilometers of the 30-km trip). A practical implication of this finding is that station stopping demands more attention from the driver than enroute control and therefore special aiding (e.g., automated station stopping) may be necessary for station stopping.
3. Evaluation of Preview, Predictive, and Advisory Aiding

Table 3.7 Comparison of Tracking Errors Between Enroute and Approaching Station. (by Display)

<table>
<thead>
<tr>
<th>Mean Error</th>
<th>Display</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Basic</td>
<td>Predictor</td>
</tr>
<tr>
<td>Enroute*</td>
<td>2.0</td>
<td>1.9</td>
</tr>
<tr>
<td>Approaching Station**</td>
<td>0.8</td>
<td>0.9</td>
</tr>
</tbody>
</table>

* Enroute is the span from the origin station to kilometer post 29.
** Approaching Station is the range from kilometer post 29 to the destination station (kilometer post 30).

Third, subjects had performed at different levels on the secondary task, but it may have been for a variety of reasons. A significant difference in the mean tracking errors across the subjects was found by the repeated measures ANOVA ($p \leq 0.05$). Table 3.8 shows the mean tracking errors of each subject with the three displays relative to the minimum of all subjects and all displays (subject 10 with the predictor display, minimum mean tracking error 0.36). Higher spare visual capacities, for example, were observed for subjects 1, 3, and 11 than for subjects 4 and 6. A practical implication of this result would be on driver selection. A person with high spare visual capacity certainly could attend to more information and improve situation awareness which would, in turn, lead to increased safety.

Table 3.8 Relative Tracking Errors (% above the minimum*)
(by Display and Subject)

<table>
<thead>
<tr>
<th>Subject</th>
<th>Display</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Basic</td>
<td>Predictor</td>
</tr>
<tr>
<td>1</td>
<td>139</td>
<td>280</td>
</tr>
<tr>
<td>2</td>
<td>11</td>
<td>45</td>
</tr>
<tr>
<td>3</td>
<td>460</td>
<td>386</td>
</tr>
<tr>
<td>4</td>
<td>11</td>
<td>42</td>
</tr>
<tr>
<td>5</td>
<td>497</td>
<td>404</td>
</tr>
<tr>
<td>6</td>
<td>4</td>
<td>43</td>
</tr>
<tr>
<td>7</td>
<td>35</td>
<td>85</td>
</tr>
<tr>
<td>8</td>
<td>22</td>
<td>25</td>
</tr>
<tr>
<td>9</td>
<td>16</td>
<td>28</td>
</tr>
<tr>
<td>10</td>
<td>40</td>
<td>0</td>
</tr>
<tr>
<td>11</td>
<td>236</td>
<td>395</td>
</tr>
<tr>
<td>12</td>
<td>40</td>
<td>103</td>
</tr>
</tbody>
</table>

* The minimum, 0.36, is taken among mean tracking errors of all subjects with all displays and was achieved by subject 10 with the predictor display.
3. Evaluation of Preview, Predictive, and Advisory Aiding

B: the basic display in routine speed control
P: the predictor display in routine speed control
A: the advisor display in routine speed control
A2: the () display in routine speed control with secondary task

Figure 3.15 Comparison of Performance Between Runs of Routine Speed Control And Runs of Speed Control with Secondary Task (Organized by Display and Run Type).
3. Evaluation of Preview, Predictive, and Advisory Aiding

Figure 3.16 Tracking Errors of the Secondary Task by Subject 11.
3.4.10 Workload: Immediate and Absolute Ratings

3.4.10.1 Time Pressure, Mental Effort, and Stress

After each test run, the subject was asked to rate the workload of the run in terms of time pressure, mental effort, and stress on a discrete scale from 1 to 7 with increasing loading (Appendix N). Distributions of the ratings on the three measures are presented in Figure 3.17 for the runs of routine speed control.

**Time Pressure.** The displays had no significant impact on time pressure, as expected. In fact, subjects were observed not showing any indications of busyness or overlapped activities in runs with routine speed control ($F_{(2, 22)} = 0.937, p = 0.37$).

**Mental Effort.** Ratings on mental effort were significantly different across the displays ($F_{(2, 22)} = 9.72, p = 0.0005$). In particular, subjects rated mental effort with the predictor display ($\bar{X} = 3.17$ on a scale of 1 to 7) and the advisor display ($\bar{X} = 2.96$) significantly lower than that with the basic display ($\bar{X} = 4.42$) (Scheffé's test, $p < 0.005$). The aided displays relieved the subjects from mentally estimating braking curves and extrapolating future speed response, and relieved them from intensively searching for landmarks within the fast flowing visual field. Therefore, low mental demand was involved in the speed control task with the aided displays. This was especially true with the advisor display, where subjects, with the aid of the predictor, followed the optimal speed profile explicitly displayed to them. In contrast, without these aids, more mental effort was required to perform the same task as evidenced both by subjects' ratings of mental effort with the basic display and by subjects' comments provided in the exit questionnaire (Section 3.4.12).

**Stress.** Aiding had a strong effect on subjective rating on stress ($F_{(2, 22)} = 7.13, p = 0.0025$). In particular, subjects perceived significantly less stress with the advisor display ($\bar{X} = 2.67$ on a scale of 1 to 7) than with the basic display ($\bar{X} = 3.83$) (Scheffé's test, $p = 0.003$). Stress with the predictor display ($\bar{X} = 3.08$) was rated much lower than that with the basic display (Scheffé's test, $p = 0.06$). At least six subjects commented that the basic display left a feeling of uncertainty about speed compliance, station stopping and control under emergency conditions. These uncertainties created stress.

Table 3.9 summarizes the mean ratings on time pressure, mental effort and stress associated with the displays. The trend of decreased mean rating on workload in all three
measures with the increase in aiding level is apparent in Table 3.9. It should also be noted that the maximum mean rating on workload was only 4.4 on the rating scale from 1 to 7 with increasing loading.

<table>
<thead>
<tr>
<th>Workload Measure</th>
<th>Basic</th>
<th>Predictor</th>
<th>Advisor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time Pressure</td>
<td>3</td>
<td>2.5</td>
<td>2.4</td>
</tr>
<tr>
<td>Mental Effort</td>
<td>4.4</td>
<td>3.2</td>
<td>3.0</td>
</tr>
<tr>
<td>Stress</td>
<td>3.8</td>
<td>3.1</td>
<td>2.7</td>
</tr>
</tbody>
</table>

The above results of subject ratings must be taken with a dose of caution, however. Studies [Tsang 1994] have shown that subjective rating via an immediate-absolute method such as this is usually correlated with subjects' performance in the particular run just completed, and thus can be biased (hence the retrospective and relative measures of subjective workload were also assessed as discussed later in this chapter). For example, that the stress with the predictor display does not show a significant difference from that with the basic display is inconsistent with the subjects' comments provided in the exit-questionnaire. Subjects uniformly welcomed the predictive aids (Section 3.4.12).
Figure 3.17 Workload: (a) Time Pressure, (b) Mental Effort, and (c) Stress.
3.4.10.2 Sensitivity of Workload to Additional Tasks

For each display, paired t-tests were conducted (between runs of routine speed control and those with the secondary task) on ratings of time pressure, mental effort, and stress (Figure 3.18). The results, summarized in Table 3.10, show that (1) the advisor display was the most sensitive to the additional task in both mental effort and stress, (2) the basic display was the least sensitive to time pressure, and (3) workload with the advisor display was significantly affected by the additional task in all three measures ($p \leq 0.023$) as shown in the right-most column of Table 3.5.

It was unexpected, however, that subjects felt that with the predictor and the advisory displays the additional task increased their mental effort ($p \leq 0.023$ and $p \leq 0.001$ respectively) more than with the basic display ($p \leq 0.43$). This surprising result may be explained by the dependencies of the three workload measures. With the presence of the secondary task, subjects felt more attention competition when the aided displays were presenting more information for them to attend. Although such competition of visual attention was not significant, as the secondary task was shown to be non-invasive, it left subjects less time to keep track of details of the aided displays and associated optimal throttle maneuvers. This time pressure was transformed into intense mental effort in just using the aids, as a result of performing the same amount of mental work in the reduced available time. Therefore, it was the time pressure that made the mental effort seem much higher to the subjects. The fact that the advisor display produced very small $p$ values ($p < 0.02$) across all three measures of workload lends extra weight to this explanation. Of the three displays, the advisor display demanded the most attention for subjects to follow the optimal profile closely. Thus, for the predictor and advisory displays, the rating on mental effort under the presence of the secondary task was significantly higher than that without the secondary task.

<table>
<thead>
<tr>
<th>Table 3.10</th>
<th>$p$-Values† by Paired t-Tests Comparing Runs of Routine Speed Control to Runs with Secondary Task (By Display)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Workload Measure</td>
<td>Basic</td>
</tr>
<tr>
<td>Time Pressure</td>
<td>0.017*</td>
</tr>
<tr>
<td>Mental Effort</td>
<td>0.429</td>
</tr>
<tr>
<td>Stress</td>
<td>0.026*</td>
</tr>
</tbody>
</table>

† The $p$-value is the probability of rejecting a hypothesis when it is true.
Figure 3.18 Comparison of Workload Between Runs of Routine Speed Control And Runs of Speed Control With the Secondary Task. (a) Time pressure, (b) Mental effort, and (c) Stress. (O2—the () display in runs of speed control with the secondary task.
3.4.10.3 Sensitivity of Workload to Operation Conditions

Paired t-tests on ratings of time pressure, mental effort, and stress between runs of routine speed control and those with emergency scenarios (Figure 3.19) were conducted for each display. The results, summarized in Table 3.11, show that no significance was found on time pressure for any display. This was expected. Before the emergency signal event, the operation condition was exactly the same as that of routine speed control. Once the event occurred, except at the moment of initiating braking in response to the perceived signal change, subjects had sufficient time to exercise any control application to avoid a potential red-light overrun.

As for mental effort, although subjects' ratings indicated that mental effort was significantly increased by the emergency condition only with the predictor display ($p = 0.027$), the trend of increased mental effort in the emergency situation was evident for all displays.

As expected, subjects felt significantly stressed by the emergency condition for all displays ($p \leq 0.01$). The suddenness of the event and the psychological suspense about the outcome to his or her control were all factors that could have contributed to the stress.

<table>
<thead>
<tr>
<th>Workload Measure</th>
<th>Basic</th>
<th>Predictor</th>
<th>Advisor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time Pressure</td>
<td>0.232</td>
<td>0.247</td>
<td>0.220</td>
</tr>
<tr>
<td>Mental Effort</td>
<td>0.137</td>
<td>0.027*</td>
<td>0.118</td>
</tr>
<tr>
<td>Stress</td>
<td>0.007*</td>
<td>0.012*</td>
<td>0.007*</td>
</tr>
</tbody>
</table>

* The $p$-value is the probability of rejecting a hypothesis when it is true.
3. Evaluation of Preview, Predictive, and Advisory Aiding

Figure 3.19 Comparison of Workload between Runs of Routine Speed Control And Runs With Emergency Signal Event. (a) Time Pressure, (b) Mental Effort, and (c) Stress.

()2—the () display in runs of speed control with the secondary task.

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3.4.11 Overall Workload: Retrospective and Relative Ratings

Subjective workload was also assessed using a retrospective-relative method. The exit-questionnaire asked subjects to rate overall workload of the displays given that the workload associated with the basic display was assigned a value of 100. The overall workload ratings for each display, scaled with the highest value being 100 for each subject, are plotted in Figure 3.20.

The overall workload was found to be different both across all displays ($F_{(2, 22)} = 31.233, p < 0.0001$) and between any two displays (Scheffé's test, $p \leq 0.05$). In particular, most subjects (83%, 10 out of 12) rated the basic display as imposing the highest overall workload ($\bar{X} = 100$), and the advisor display the lowest workload ($\bar{X} = 56$), with the predictor display in the middle ($\bar{X} = 70$). However, one subject thought that while the basic display imposed a higher workload than the two aided displays, the advisor display imposed a higher workload than did the predictor—contrary to the majority. He explained that the constraint of following the advisor exerted more attention load. Further, another subject rated the advisor display as imposing a higher workload than either the basic or the predictor display. He explained that closely following the optimal profile in the advisor display took more attention than driving with the other displays.

![Figure 3.20 Ratings on Overall Workload.](image-url)

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3.4.12 Preference on Displays

Subjects' rankings of the displays were also collected in the exit questionnaire and are summarized in Table 3.12. Seventy-five percent of subjects (9 out of 12) chose the advisor display as their first choice; 67% (8 out of 12) chose the predictor display as second, and an overwhelming majority (92%, 11 out of 12) made the basic display the least preferred choice. Further, no subject preferred the basic display as his or her first choice; nor did any subject deem the advisor display the last choice.

These differences in ranking across all displays exhibit significance with $p < 0.01$ by the Friedman two-way analysis of variance by ranks ($F_r = 17.17, k = 3, N = 12$). Further analysis reveals significant differences in mean rankings between the basic and the predictor displays ($p < 0.01$), and between the basic and the advisor displays ($p < 0.0005$); no significant differences were found between the predictor and the advisor displays ($p = 0.12$). This finding suggests that (1) subjects' preference of the predictor or the advisor to the basic display was significantly strong, (2) the difference in ranking between the predictor and the advisor displays, although large, is not enough to permit a conclusion that these two displays were ranked differently.

<table>
<thead>
<tr>
<th>Display</th>
<th># of times ranked first</th>
<th># of times ranked second</th>
<th># of times ranked third</th>
<th>Modal Rank</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basic</td>
<td>0</td>
<td>1</td>
<td>11</td>
<td>3</td>
</tr>
<tr>
<td>Predictor</td>
<td>3</td>
<td>8</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Advisor</td>
<td>9</td>
<td>3</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>

The subjects' comments in the exit questionnaire provided explanations about their choices. In general, the preview and predictive aiding received consistently positive comments by all subjects. The three predictor curves and the signal preview were especially mentioned among the desirable attributes of the predictor and the advisor displays. These aids were helpful particularly in the emergency situation and in station stopping.

The advisor display provoked contrasting comments from the subjects. Most subjects liked the advisor display for various reasons: "easy to follow", "allowing more time to look at the signals", "letting me see exactly what the next operation will be", "letting me know if I am efficient and on time", and so on. Two of the three subjects who did not rate the
advisor display as their first choice explained that "the advisor was too strict", or "I knew the track very well [through training] and did not need the advisor". (The third subject thought the advisor was difficult to follow due to its "insufficient resolution"). These reasons are attributable to the subject's self-imposed strictness in using the advisor display.

Eleven out of the 12 subjects most disliked the basic display because (1) it did not provide sufficient advance information, (2) it was difficult to estimate or calculate (in their mind) the stopping distance or the braking curve, (3) it involved too many human errors due to uncertainties in judging the necessity of emergency braking. The subject who preferred the basic to the predictor display explained that "I really liked the basic [display] after learning the visual cues. It made it more like driving, while both of the others made me concentrate a lot more on the control panel.... Safety-wise, I liked the predictor [display] over the basic [display]...." This subject, however, preferred the advisor display, the one that seems to induce the most head-down time, as his first choice because "it really simplified the train operation and allowed me to relax through most of the trip...."
3.5 SUMMARY

Major results from the experimental investigation of predictive and advisory aiding are summarized as follows:

(1) A number of measures associated with safety were shown to be improved with both the preview aiding and the predictive aiding. The preview aiding increased subjects' situation awareness; the predictive aiding improved quality of decision making. In addition, schedule adherence and station-stopping accuracy were shown to be consistently better with the aiding than without.

(2) The advisory aiding led to significantly less total cost (that of energy consumption plus a weighted schedule deviation) than the basic and the predictor displays. The advisor display left subjects the least amount of spare visual capacity, but was preferred by most subjects. Further, subjects rated the advisory display as incurring the lowest overall workload.

(3) The basic display imposed the highest overall workload and was the least preferred. However, it offered the most spare visual capacity, and is therefore the least sensitive in time pressure to additional tasks.

(4) Workload (time pressure, mental effort, and stress) associated with the advisor display was found to be the most sensitive to additional tasks as compared with those associated with the basic and the predictor displays.

(5) For all displays, stress level was the most affected by operational conditions.

Implications of these findings will be discussed in Chapter 5.
CHAPTER FOUR

EVALUATION OF PREDICTIVE AIDING BY MODEL SIMULATION

4.1 INTRODUCTION

An alternative method for evaluating displays is through simulation with a model of the driver. The main advantages of human models in the context of this research are threefold. (1) Models provide a flexible tool to systematically analyze the effects of display information on system performance. (2) They allow prediction of system performance under various information displays to be achieved in shorter time and at lower cost. Therefore, models may be used to provide early and preliminary evaluation of competing configurations without the necessity for expensive human-in-the-loop experiments.

There are two types of human models: a *normative* model, which describes what the human should do according to some assumed criterion, and a *descriptive* model, which attempts to fit experimental data (or describe what the human really does). This research developed a rule-based normative model of the train driver or engineer, with one parameter fitted with the human-in-the-loop experimental results reported in Chapter 3. It is normative because the rules were those used in training the subjects for the experimental tests.

The purpose of the model was to extend the experimental results to conditions which have not been tested with the human-in-the-loop simulator experiment. In particular, a model-in-the-loop simulation was conducted to predict driver responses to a dynamic signal event with either the basic display or the predictor display, wherein changes in the signal were
induced by a moving lead train (as opposed to the unknown but in fact stationary object in the human-in-the-loop experiment).

The reason behind the choice of a rule-based model was fourfold. First, the relatively few driving rules are simple compared to the more complicated dynamic system operations characteristics of, e.g., airplanes. Second, driver knowledge obtained from training, e.g., route characteristics, could not be naturally incorporated into non-rule-based models. Third, the necessary preview behavior in train driving precludes the use of the well-studied servomechanism models (Section 1.3.3). Fourth, rule-based modeling easily allows dealing with nonlinear and time-varying dynamics of the train.

4.2 OVERVIEW OF THE MODEL

Major assumptions underlying the driver model are as follows:

1. The driver is sufficiently well-trained and motivated to perform in a near optimal manner, subject to system goals and limitations. He or she is well-trained in the knowledge needed to handle the train with both the optimal and the max-max control strategies.

2. Human limitations such as perception time delay and noise, information processing delay and inaccuracy are negligible compared to the train dynamics time constant, with only one exception—the time delay in perceiving changes in signal.

3. The alert system does not interfere or affect the speed control performance and thus can be neglected in modeling the driver's task. This assumption is supported by the experimental result that all subjects responded to the alert system in time without being penalized by the alert system.

The model is an integration of two independently functional, normative models, referred to as the optimal model and the max-max model. The top-level functional structure of the model is illustrated in Figure 4.1. The optimal model is, in fact, a direct implementation of the optimal control solution whose corresponding optimal speed profile was used for the advisory aiding. The max-max model was an implementation of a set of control rules the driver must use when the optimal control strategy is not available. In practice, the optimal strategy could be unavailable either because the driver has never been taught an optimal strategy or because an emergency maneuver enroute forced the train to deviate from the optimal trajectory and, as a result, the rest of the optimal strategy becomes no longer
optimal. A third possibility arises from the inaccuracy of the optimal model used to obtain the optimal control strategy. In this case, deviation of the train from the optimal trajectory would be a gradual process, even if the driver has followed the optimal strategy precisely. A remedy for this could be provision of an update of the optimal solution after the deviation exceeds a certain tolerance. In the case of an emergency maneuver, however, it may be impractical, if not impossible, to provide continuous update of the optimal trajectory under dynamic situations such as those created by an unexpected moving lead train. Upon the invalidation of the optimal control rules that the driver has relied on in routine operations, the driver would resort to a survival strategy which is modeled to be the max-max strategy in the simulation model described here. In particular, the emergency situation under this model study is an unexpected change in signal that calls for an immediate abandonment of the optimal trajectory and a resort to the max-max control strategy.

The max-max control strategy can be simply summarized by the following rule: apply maximum traction when an acceleration is called for, or maximum braking when a deceleration is called for—under the constraints of ride quality; otherwise, cruise with a force just balancing the friction. Decision-making with this rule involves using knowledge or experience a driver has learned during training and previous journeys. Four functional components of the knowledge base are depicted in Figure 4.1, each of which has its own role in decision making. The *train traction/braking characteristics* are crucial for estimating the moment or location to initiate braking to reduce the speed of the train below the speed limit ahead. The *train-handling technique* reflects the driver's skill at throttle manipulation under the constraint of ride quality. The *route characteristics* are major "points of no return" for cueing important control actions. The *schedule* is used to compensate for schedule deviation in the control decision-making rule. A detailed diagram of the rules is included in Appendix P.
4. Evaluation of Predictive Aiding by Model Simulation

Figure 4.1 Integration of Two Control Strategies in the Driver Model. The blocks with a heavy frame (■) are functions whose lower level decompositions are illustrated in separate diagrams (Appendix P)

4.3 APPLICATION OF THE MODEL

The developed model was applied to extend the findings of the human-in-the-loop experiment by investigating effects of display on safety, under a dynamic event wherein the signals were activated by a moving lead train instead of by a motionless object. The scenario is as follows. The train starts with the optimal control strategy along the test course (same as that in Chapter 3). When it reaches KP14.6 with a speed of 250 km/h (on the optimal trajectory) and an acceleration with 90% of full tractive effort, a change in signal aspect of block 7 (where the train is located) from GGG ("proceed") to GYG ("proceed approaching next signal at 220 km/h") occurs. The signal change is activated by a leading train appearing at KP22 (as a result of red-light overrun, for example) with a speed of 250 km/h and a deceleration with full-service braking. The leading train slows down to 70 km/h when reaching KP27.2 and maintains the speed of 70 km/h.
The following train, i.e., the train governed by the driver model, reacts to the event only after perceiving the signal change. The times of reaction to such an event have been measured from the human-in-the-loop experiment (Section 3.4.3) for the basic display ($\bar{X} = 8.6$ seconds) and the aided display ($\bar{X} = 1.4$ seconds). These average reaction times are used as the delay in the perception of a signal change—the only time delay considered in the perception component of the model (Figure 4.1).

Figure 4.2 compares the responses of the model with the basic display and the predictor display under the dynamic signal event described above. In particular, comparing responses around KP14.6 (when signal change occurred) between the basic and the predictor displays, we can observe that, with the basic display, the "driver" was unaware of the signal change and continued accelerating according to the optimal strategy until some distance later (after 8.6 seconds). It was then too late to avoid excessive overspeed and the train incurred emergency braking. In contrast, with the predictor display, the "driver" responded to the signal change quickly (with a delay of 1.4 second) and could safely maneuver the train under the dynamic signals caused by the lead moving train.

In summary, the investigation by simulation with a driver model further shows that the predictive aiding is capable of improving safety in terms of speed compliance and timely response to unexpected signal events. The model simulation results support the finding of the human-in-the-loop experiments, that the predictive aiding offers not only increased safety, but also other benefits of reduced emergency braking—no injuries to passengers or damage to equipment, shorter delays in schedule and less energy consumption.
4. Evaluation of Predictive Aiding by Model Simulation

Figure 4.2 Responses to Dynamic Signal Event By Model With the Basic And the Predictor Displays.
CHAPTER FIVE

CONCLUSIONS

5.1 SUMMARY

Three decision aids for drivers in control of high-speed trains were proposed, then designed as three integrated cab displays. The three displays are the preview display (a profile of speed limits, signals, track geometry, and so forth, for up to 20 km ahead), the predictor display (preview plus curves to show speed-distance responses for emergency and full-service braking, and for present propulsion or braking level), and the advisor display (predictor plus a minimum-energy trajectory that meets speed limits, schedule, and ride quality requirements. These were realized as cab displays in a high-speed rail system simulator. Formal human-in-the-loop experiments were conducted to evaluate effects of these displays on driver-train system performance. An implementation of a conventional high-speed train cab environment, referred to as the basic display, was used as a baseline for comparison purposes.

The following are the major conclusions reached from the experimental results and are the most significant contributions.

1. The preview was found to extend drivers' capability of looking ahead for signals and speed limits and, therefore, allowed fast reaction and increased signal detection capability. This finding is supported by three facts. First, subjects had significantly shorter time of reaction to unexpected changes in signal. Second, subjects had improved speed compliance with the preview display as a result of being aware of the upcoming
5. Conclusions

in civil speed limit. Third, subjects consistently preferred the preview display over the basic when choosing between the two.

2. The predictive aiding offers significant promise in increasing safety through improving the quality of decision making both in handling unexpected emergency situations and in normal conditions. When an unexpected change in signal occurred, subjects could initiate emergency braking, when necessary, at the lowest possible speed without committing red-light overrun. This conclusion is strongly supported by both the experimental investigation and the demonstration with the model simulation.

In addition, the predictor curves helped subjects make informed control decisions in normal operations. First, with these aids, subjects could avoid excessive braking that would not only incur high energy consumption, but also lead to late arrival at the station. The aids were also found to guide subjects to apply needed braking in time to avoid speed infraction. Second, subjects were relieved of the mental effort of estimating the amount of necessary braking which, in turn, reduced subjects' stress from the high uncertainties involved in the estimation process. This finding is strongly supported by (1) subjects' ratings on workload measures obtained by both an immediate-absolute method and a retrospective-relative method, and (2) subjects' consistent comments (provided in an exit-questionnaire) on the predictor's strong aiding effect on their decision making and correspondingly reduced human error in decision making.

3. The advisor display was found to improve energy consumption significantly over all other displays studied. However, there is no significant difference between subjects' preference for the advisor display versus the predictor display, although both were consistently preferred over the basic display. Most subjects (75%) preferred the advisor display to the predictor or the basic display, while the others disliked the advisor display and preferred the predictor display with reasons attributable to the high constraints of the advisor in control manipulation. Nevertheless, subjects rated the advisor display as having the lowest overall workload.

4. As a result of the improved control decision making with predictive aiding (the predictor curves), both the predictor and the advisor displays were found to significantly increase station-stopping accuracy and schedule adherence. The full-service braking curve was found to be an effective aid for station stopping. It relieved subjects' mental effort in estimating the necessary amount of braking, and let subjects perform station stopping
with assurance and relative ease as compared to the basic display. Similarly, the aids allowed subjects to avoid excessive braking and, hence, late arrival.

5. The predictor and the advisor displays were also found to have the potential for reducing driver training time. This was evidenced by the much steeper learning curves associated with these two displays than those with the basic display in measures including speed compliance, energy consumption, station-stopping accuracy, schedule adherence, and passenger ride quality.

6. The benefits of the aiding, however, may come at a cost. The aided displays tended to incur more "head-down" time than the display without these aids—subjects concentrated more on the cab displays as more information was presented in the aided displays. This finding was supported both by the subjects' performance on a secondary task designed to measure visual spare capacity and by the subjects' comments provided in the exit questionnaire. More concentration on the provided aiding implies less attention to tasks other than speed control. A practical implication from this finding is that more aiding should be realized only when all important information can be included in cab displays and can be attended to by the driver even with the aids present.

In spite of this tendency of increased "head-down" time with the increase in aiding, the aided displays were not found to overload the subjects, either in routine speed control or in speed control with a continuous tracking task.

In addition to the above major results, other findings include (1) station-stopping demanded significantly more visual attention with any display than en-route control, and (2) subjects performed at widely different levels in tasks besides speed control. The former indicates that some special aiding may be necessary for station stopping; the latter suggests the importance of visual capacity as a criterion in driver selection.
5.2 FUTURE RESEARCH

1. Further research is needed to investigate how to take advantage of the benefits associated with the proposed aids while in the mean time eliminating the associated side effects, i.e., those induced by the increase in head-down time.

2. An experiment with real locomotive engineers would be able to provide more insight on the use of and potential improvement of the proposed aids.

3. Since station stopping was found to be significantly more demanding of visual attention than enroute control, it may be worth investigating automation for station stopping (e.g., programmed stopping) in connection with the use of the predictor and the advisor displays.

4. As mentioned in the introduction, there are two options in aiding the human: more decision aids like those presented in this research, or more automation. Although the direction of this thesis has been in decision aiding, the algorithm developed for the optimal solution for a minimum-energy control of a given trip may be implemented for fully automatic control of the train [Yin and Sheridan 1994]. The same algorithm could be applied to provide solutions for the "programmed stopping" mentioned above. Maybe a combination of the decision aids presented here with some automation could be a better human-machine allocation design. This is a challenging issue for future research.
REFERENCES


Miller, R. A. 1967. *A preview control model with one or two fast time scale loops.* MS Thesis. Department of Mechanical Engineering. Massachusetts Institute of Technology.


References


APPENDIX A

THE VOLPE CENTER HIGH-SPEED TRAIN SIMULATOR

A.1 MOTIVATION

An important approach to human factors research is experimental investigation. For obvious safety and logistic reasons, however, prototypical or field experiments are often not feasible. Instead, a computer simulated environment is suitable, flexible and cost-effective.

As such, a real-time, interactive, and distributed high-speed rail system simulator has been developed for the Volpe National Transportation Systems Center (VNTSC) to study human factors issues associated with the operation of high-speed trains. The simulator, developed on Silicon Graphics workstations, emulates displays and functional components inside a cab as well as the Central Traffic Control (CTC) environment. The simulator was initially used to investigate effects of decision aids on driver-train performance. It is now being used to study effects of automation and will later be used for investigations of various human factors issues involved in operation of high-speed rail system.

It should be noted that the implemented system is a mix of existing high-speed rail systems such as the French TGV and the Japanese Shinkansen. The simulator does not (and was not intended to) replicate any existing system. However, the train dynamics and the signal system were modeled after those of a French Atlantic TGV.

A.2 FUNCTIONAL REQUIREMENTS

Development of the high-speed train simulator required a selection of a signaling system. Although future signaling use "moving blocks" (which can be realized with the global positioning system), a fixed block signaling system was chosen because of its current existence for both freight and high-speed passenger trains.

The need to test many different prototypes of decision aids or displays demanded rapid reconfigurability of the cab-driver interface. This requirement was achieved in two ways: (1) by simulating the graphical displays on a Silicon Graphics workstation, and (2) by writing the simulation software in a modular fashion—different train dynamics can be
writing the simulation software in a modular fashion—different train dynamics can be implemented by recoding or replacing the appropriate modules, and different displays can be reconfigured by command-line options.

The control interface was provided via a dual-use throttle that was programmed to be capable of exerting both braking and propulsion, depending on which half of its throw the throttle is positioned. The throttle has a center notch to provide tactile feedback on its functional position (braking vs. propulsion).

Simulation of the interaction between a driver and other onboard systems required more controls. To reduce development cost and time, the computer keyboard was used for controls not related to speed manipulation. No other hardware was involved.

A.3 SIMULATOR MODULES

A.3.1 Overview

As shown schematically in Figure A.1, the full VNTSC High-Speed Train Simulator consists of three Silicon Graphics workstations and three control mechanisms (throttle, computer mouse and keyboards) to emulate cab displays, out-the-window view, and Central Traffic Control (CTC). One workstation is used to display the cab indicators and instruments, to compute dynamics of the train, and to conduct computations associated with the decision aids. Another workstation emulates the out-the-window view and is physically placed side by side with that of the cab displays. The third workstation is used as a Central Traffic Control workstation. The throttle is connected via an A/D converter to the serial port of the workstation. All three workstations exchange data through a local-area-network link.

It should be pointed out that the CTC simulation can control multiple trains, although only one train simulation is shown under the control of the CTC in Figure A.1. In addition, the out-the-window view can be emulated and displayed (by a command-line configuration) in the same workstation as the cab displays. This configuration, however, tends to reduce the effectiveness of the out-the-window view due to its small screen area (one fourth of the workstation screen). Further, the cab display and the out-the-window view can be simulated without the use of CTC simulation, either as one module in one workstation or as two modules in two separate workstations. Such a configuration of the simulator may
only be used for experiments where no communication between the driver and the dispatcher is required. Figure A.1 shows the primary simulator configuration used for the experimental investigations conducted for this thesis research and is further described here.

**Figure A.1 VNTSC High-Speed Train Simulator.** The simulator includes three workstations, a dual-use throttle, computer mouse, and keyboards. The workstations are connected by a local-area-network (LAN) link. The throttle is interfaced through an analog-digital converter to a serial port of the workstation simulating the cab displays.
A.3.2 Functional Components and Instrumentation

*Cab Displays*

Instruments and indicators in a basic simulated cab display, shown in Figure A.2, include a speedometer, cab signal, automatic train protection (ATP) system, alert system, door open/close indicator, force-level indicator, call-up schedule display, text message input and output displays, and other onboard subsystem indicators such as braking pipe pressure, electric power level, and so on.

The speedometer, located in the center region of the screen, indicates current speed, speed limit of the current block, and speed limit of the next block. To the upper right of the speedometer is the cab signal consisting of three colored lights. Each of the lights may be \( G — green \), \( Y — yellow \) or \( R — red \) at certain times depending on the track condition ahead (e.g., being occupied at some distance away).

Geometrical information about the current location of the train is provided below the speedometer. The grade (in degrees) of the track at the current location is shown under the speedometer. The number of the block where the train is currently located and the number of the kilometer-post that the train has just passed are shown below the lower right corner of the speedometer with the symbols BL followed by the block number and KP followed by kilometer post number. In addition, the distance to the next station is displayed to the lower right of the block number (outside the frame of the central region). Under the distance to the next station is the current time.

The control interface between the driver (subject) and the train simulator was provided via a dual-use throttle that was programmed to be capable of applying both braking and traction, with each function allocated one half of the throttle throw. The throttle has a center notch to provide tactile feedback on its functional position (braking vs. traction).

The indicator corresponding to the dual-use throttle is a horizontal grid bar located under the frame of the central region in Figure A.2. The center grid of this indicator corresponds to the center notch position of the throttle. Functionally, this position of the throttle is neutral; no braking or traction is applied. To the left of the center grid, braking is displayed; to the right, traction level. The throttle is capable of continuous force application (as compared to notched levels) and its indicator is displayed accordingly. The grid lines
on the force indicator are provided as measures of force level at every 10% of the maximum braking or traction.

Functions related to speed control are provided on the right side of the screen of the cab display simulation computer. Two functions are shown in Figure A.1: the automatic train protection (ATP) system and the emergency stop (although other functions such as cruise control, automatic control, and programmed station-stopping are available in the simulator). The emergency stop can be activated manually either via a press on the keyboard (F12 key) or via a mouse-click on the emergency-stop indicator. The ATP system warns the driver (by blinking its triangular indicator) when the speed of the train is above the speed limit. It automatically activates the emergency stop when (1) the train is excessively overspeed—more than 15 km/h above the speed limit, or (2) the speed of the train is in the warning zone (within the 15 km/h overspeed tolerance) for more than 20 seconds. Emergency braking, whether activated manually or automatically, cannot be reset until the train has fully stopped.

To the lower left of the speedometer (outside the central region) is the door status indicator. The door can only be opened or closed by a click on the door display to toggle the door open (red) or close (gray) when the train is not moving. Conversely, the train cannot move unless the door has been closed.

The status display of the alert system, located just under the door indicator, generates a blinking-yellow warning. The warning is activated with a random period in the range from 40 to 80 seconds. Once the warning is active, the alert system expects an acknowledgement or response from the operator. The response could be either a press on the keyboard (Esc) or a throttle maneuver. If no response is received in 10 seconds after the initiation of the warning, the alert status display changes to blinking red accompanied by beeps. If no response is received in another 10 seconds, emergency braking is automatically activated. Again, emergency braking cannot be reset until the train has come to a complete stop.

A call-up schedule display is provided at the lower left of the workstation screen. The schedule, which can be shown or hidden by a mouse-click on the schedule button, consists of arrival, departure, and station-stopping times for each station and the distances between stations on the journey.

On the right of the call-up schedule display are the incoming and outgoing message areas. The in-coming messages from the dispatcher at the Central Traffic Control are displayed in
the CTC MSG: area, with the most recent message at the bottom of the area. (Other messages are scrolled upward). The driver can type a message at the MSG: area and send it to the dispatcher with a mouse-click on the send button (at the far right of the MSG: area).

Other onboard subsystems are displayed on the right side of the workstation screen. Other displays for subsystems, such as a side task or ride quality, can be rapidly prototyped using these display areas.

Out-The-Window View

An abstract out-the-window night view is provided as a means of cueing the subject about important locations or "points of no return." A program called OTW was developed to draw a simulated night view along the track.

CTC/Experiment Control Workstation

The CTC workstation (Figure A.3) is used for the dispatcher or the experimenter to monitor the progress of the train's motion, to control the path of the train, and to communicate with the driver. A mouse-based graphical user interface, supported by software module CTC, provides the ability to select a specific region of interest for inspection, to determine location of the train or trains, and to turn a switch to a desired direction which, in turn, affects the route of a train. Communication between the dispatcher or experimenter and the driver or the subject is through keyboard-typed messages, simulating a standard CB radio system. The simulated messages are transmitted between workstations via a local-area-network link.

An important function of the CTC workstation is to coordinate the simulation modules, i.e., cab displays, CTC, and OTW, for real-time simulation. In the main experiment reported in this thesis (with decision aids) this workstation was used solely for simulation control and for the experimenter to monitor the progress of the subject.

A.3.3 Rapid Prototyping Capabilities

The simulator was created in the C programming language with Silicon Graphics Library primitives. This method of implementation allows the cab displays to be rapidly reconfigured or redesigned to meet the varying demands of experimental studies. New displays, i.e., various levels of information aiding or automation, may be configured with a set of command-line options.
Two additional programs were written as tools for developing and using the simulator. First, a program was developed for flexible and rapid creation of a track network. The software, called Pathnet, allows the user to interactively create and modify track physical characteristics including grades, curvature, landmarks, civil speed limits, and so forth. The output of Pathnet is a database to be shared during the simulation by all three modules of the simulator, i.e., cab displays, CTC, and OTW. In addition, a UNIX C Shell program called Optimal was written to obtain an off-line solution to the minimum-energy control problem for a given trip.

Scenarios such as unexpected changes in signal aspect or preview failure can be simply configured with command-line options. Easy configuration of other scenarios such as a lead moving train can be provided by manipulating proper command-line options.
Appendix A The VNTSC High-Speed Train Simulator

Figure A.2 Primary Cab Instrumentation and Indicators. 1: Current speed  2: Civil speed limit of current block  3: Civil speed limit of next block  4: Signal of current block  5: Current kilometer post  6: Current block number  7: Grade of track at current location  8: Force indicator (traction or braking)  9: Distance to next station  10: Current time.
Appendix A The VNTSC High-Speed Train Simulator

Figure A.3 CTC/Experimental Control Workstation Display. The map shows the rail network under the dispatcher's control or supervision. It can be panned, tilted, and rescaled by mouse clicking on controls at the corners and sides of the map display area. Local zoom in or out can be achieved by clicking at any point of the track of interest. Detailed information about a particular location on the track network can be shown by mouse-clicking on the spot of interest.
APPENDIX B

MODEL OF TRAIN DYNAMICS

B.1 TRAINSET CHARACTERISTICS

Train parameters used for dynamics simulation in this research are from an Atlantic TGV. Pertinent train characteristics [DOT/FRA 1991] are listed in Table B.1.

<table>
<thead>
<tr>
<th>Pertinent Trainset Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum operating speed</td>
</tr>
<tr>
<td>Total train weight (loaded)</td>
</tr>
<tr>
<td>Maximum acceleration</td>
</tr>
<tr>
<td>Maximum operational deceleration</td>
</tr>
<tr>
<td>Emergency deceleration</td>
</tr>
</tbody>
</table>

B.2 TRACTION CHARACTERISTICS

Traction characteristics of the simulated train is that of an Atlantic TGV trainset under 25 kV - 50 Hz [Petit 1992], as replicated in Figure B.1.

![Traction/Resistance Characteristics](image)

*Figure B.1 Traction Characteristics of Atlantic TGV Trainset Under 25 kV - 50Hz.*
Appendix B  Model of Train Dynamics

B.3 DYNAMIC EQUATIONS OF MOTION

The dynamics of the train is based on longitudinal point-mass equations of motion. Since high-speed trains are usually short in length (about 70 meters), it is reasonable to assume that a high-speed train can be modeled as a solid mass \( m \).

Let \( x(t) \) denote the line distance traveled from the origin station, \( v(t) \) the speed of the train along the track, \( F(t) \) the tractive effort or propulsive force applied onto the train, \( R(x, v) \) train resistance. The train resistance consists of three elements: rolling resistance (including the resistance to wheels rolling on the rail, friction in the bearings on the cars, and aerodynamic drag), grade resistance, and curvature resistance. The rolling resistance is all friction and is shown in Figure B.1 as resistance to forward movement on a flat track.

The dynamic motion of the train can be described simply with Newton's second law of dynamics (See Figure. H.2).

The dynamic equations of motion are:

\[
\frac{dx}{dt} = v(t)
\]

\[
\frac{dv}{dt} = \frac{F(t) - R(x, v)}{m}
\]

where \( R(x, v) = R_{\text{rolling}} + R_{\text{grade}} + R_{\text{curvature}} \), \( R_{\text{rolling}} \) can be obtained from Figure B.1, \( R_{\text{grade}} = mg \sin(\alpha) \) with \( \alpha \) being the grade of the track and \( g \) the gravitational constant, and \( R_{\text{curvature}} = c \cdot m v^2 / r \) with \( c \) being the coefficient of friction (chosen as 0.4 for the simulation), \( r \) the radius of the track.

Figure B.2 Modeling the Motion of a High-Speed Train.
C.1 THE OPTIMAL-TRAJECTORY PROBLEM

The problem can be stated as follows: a train of mass $m$ is scheduled to depart from an origin station and to arrive at its destination station in $T$ seconds. The speed limits, grades and curvatures along the track are known \textit{a priori}. Pertinent train characteristics, e.g., tractive effort and rolling resistance (i.e., total resistance excluding those induced by curvatures and grades) as functions of speed, are assumed to be known. The problem is to find the speed profile that minimizes the energy consumption of the trip satisfying the limitations of train braking/propulsive capabilities, schedule, speed limits along the track, and passenger ride quality.

Assuming a non-regenerative braking system\textsuperscript{†}, the total energy consumption is, for convenience, simply defined as the total work done to move the train from the origin to the destination. This optimal-trajectory problem then has four constraints: three inequality constraints—train braking/propulsive capabilities, speed limits, and passenger ride quality (constraints on rate of change of acceleration); and one equality constraint—the schedule (must be on time). One seemingly apparent way to deal with the equality constraint is to consider the total time $T$ as a resource to be allocated among segments of the trip. This dynamic programming technique of allocation process, however, is inappropriate because the cost from an allocation of time to one segment of the trip depends on the allocation of time to other segments—violation of one of the basic assumptions associated with an allocation process [Bellman and Dreyfus 1962].

Therefore, the following maneuver was made in order to solve the above optimal-trajectory problem. In this technique, the equality schedule constraint is introduced into the cost

\textsuperscript{†} Calculation of energy consumption depends on the assumption on energy supply and train braking systems.
Appendix C Obtaining the Minimum-Energy Speed Trajectory

function, i.e., the cost function not only contains the cost of energy consumption, but also a cost of schedule deviation (or a weighted schedule deviation). The weight of the schedule deviation is part of the unknown to be solved so that the minimum total-cost solution is, in effect, the minimum energy-cost solution. In other words, the weight should be such that the optimal speed trajectory leads to a minimum-energy trip in exactly the scheduled time.

To mathematically formulate the problem, let us start with dividing the track into $N$ equal-length segments, as shown in Figure C.1. The length of the segments, denoted by $\Delta x$, should be so small that each segment can be characterized with constant grade and curvature. For a high-speed passenger train, the length of the train is short enough (about 70 meters) for the train to be modeled as a solid mass $m$, ignoring internal forces between the cars. Hence, the train's motion in one segment can be modeled with a constant acceleration.

For each segment $i$, $(i = 0, \ldots, N-1)$, let $v_i$ be the train's speed at location $x_i$, let $\Delta t_i = t_{i+1} - t_i$ be the time needed to traverse segment $i$, and let $F_i$ be the force applied to the train in segment $i$ (assuming the control force is constant within a segment). Further, let $w_e$ and $w$ be the weights on costs of the energy consumption and on schedule deviation, respectively. Then the speed profile that minimizes energy consumption should also minimize the following cost function

$$\text{Total Cost} = \sum_{i=0}^{i=N-1} w_e |F_i| \Delta x + w \left( \sum_{i=0}^{i=N-1} \Delta t_i - T \right),$$

where the two weights should be such that total time over the trip at the optimal speed trajectory satisfies

$$\sum_{i=0}^{i=N-1} \Delta t_i = T.$$
Appendix C  Obtaining the Minimum-Energy Speed Trajectory

The minimization is taken over the following sets of constraints:

1. \(-F_{\text{max braking}} \leq F_i \leq F_{\text{max propulsion}}(v_i^{\text{avg}})\),
   
   where \(v_i^{\text{avg}}, v_i^{\text{avg}} = \frac{v_i + v_{i+1}}{2}\), is the average speed in segment \(i\);

2. \(v_i \leq \bar{V}_i\), where \(\bar{V}_i\) is the speed limit at location \(x_i\).

3. \(\frac{a_{i+1} - a_i}{\Delta t_i} \leq \text{jerk}_\text{tolerance}\),

   where \(a_i, a_i = \frac{v_{i+1} - v_i}{\Delta t_i}\), is the acceleration in segment \(i\).

C.2 SOLUTION BY DYNAMIC PROGRAMMING TECHNIQUE

The author solved the above optimal-trajectory problem using a dynamic programming technique iteratively. The iteration was to search for the desired ratio of the two weights, \(w_e\) and \(w_r\). Since it is the cost of schedule deviation relative to that of the energy consumption that affects the time needed to travel a given distance while minimizing energy consumption, the weight on energy consumption was chosen as a constant, \(w_e = 1/1000\), for convenience. The iteration was then to find the \(w_r\) such that \(\sum_{i=0}^{N-1} \Delta t_i = T\) holds exactly for the minimum-cost trip.

The search for the proper \(w_r\) was conducted through a simple bisection method. In particular, the iteration starts with two 'guessed' \(w_r\)'s. The optimization problem is then solved for each of the "guessed" values of \(w_r\). These two values should be chosen such that one leads to an early arrival and the other a late arrival, if not on time. Then, \(w_r\) is adjusted according to the simple bisection method, i.e., the new weight is the mean value of the initial two "guessed" values, and corresponding optimal solution is obtained by dynamic programming (described below). If the time constraint is not satisfied to a tolerable level with this new weight, \(w_r\) is then adjusted and a new round of optimization by dynamic programming is executed. The process continues until a proper \(w_r\) is found, and, in the same time, the minimum-energy speed profile is obtained.
Appendix C Obtaining the Minimum-Energy Speed Trajectory

For a given $w$, the following optimization is performed. Let the cost over segment $i$ be $c_i,$

$$c_i = w_i |F_i| \Delta x + w_i \Delta t_i,$$

and let $J_i(v_i)$ denote the minimum total cost to move the train from $x_i$ to the destination of the trip, $x_N$. Then, the principal of optimality [Bellman and Dreyfus 1962] states that

$$J_i(v_i) = \min_{F_i} c_i + J_{i+1}(v_{i+1}).$$

This recursive equation can be solved with a backward dynamic programming. Let us first introduce the notation and terms necessary for describing the dynamic programming procedure.

1. **State at stage $k$**, denoted by $v_k$, $0 \leq v_k \leq \bar{V}_k$, refers to speed at location $x_k$. The continuous range of state $v_k$ is discretized into $I_k+1$ discrete values, $0, \Delta v, 2\Delta v, \ldots, I_k\Delta v$, where $\Delta v$ is a parameter chosen for the dynamic programming procedure and $I_k = \frac{\bar{V}_k}{\Delta v}$. Therefore, the states at stage $k$ can be written as $v_k = i \Delta v, \ i = 0, \ldots, I_k$.

2. Another concept to be introduced is **possible state**. Since there are constraints on control force, it may not be possible to get to $v_N$ at stage $N$ from every state $v_{N-1}$ at stage $N-1$. In this case, $J_{N-1}(v_{N-1})$ is only defined for those $v_{N-1}$ from which it is possible to get to $v_N$—the final known state of the trip. Similarly, $J_{N-2}(v_{N-2})$ is only defined for those $v_{N-2}$ from which it is possible to get to at least one possible state at stage $N-1$, and so on. Therefore, a possible state at stage $k$ is a value of $v_k$ from which it is possible to get to at least one possible state at stage $k+1$. The known state of the last stage, $v_N$, is a possible state.

3. From each state, at a given stage $k$, the cost to get to stage $k+1$ is a function of the two states,

The backward dynamic programming (Figures C.2-C.3) starts with stage $k = N-1$ since the possible state $v_N$ at stage $N$ is given or fixed. All paths from each possible state at stage $N-1$ to the final state $v_N$ are least-cost since there is only one possible state at stage $N$. The corresponding cost of the least-cost path and the acceleration from the possible state at stage $N-1$ to state $v_N$ are then stored (Table C.1) for use in the next stage.

At stage $k$, the least-cost path from each state $v_k$ to the final state $v_N$ is obtained by comparing among the costs of all paths from $v_k$ to $v_N$ via each possible states at stage $k+1$. The calculation of this total cost is simply to add the cost from $v_k$ to the possible state $v_{k+1}$
Appendix C  Obtaining the Minimum-Energy Speed Trajectory

at stage $k+1$ and the minimum cost from $v_{k+1}$ to the final state $v_N$ which has been
 calculated in the previous stage and recorded (in the form of Table C.1). In the mean time,
a new table that contains the minimum cost and the acceleration for the current stage $k$ is
 constructed while searching the least-cost path from each state $v_k$, $v_k = i \cdot \Delta v$, $i = 0, \ldots, I_k$
to the final state $v_N$.

<table>
<thead>
<tr>
<th>$v_k$</th>
<th>$a_k(v_k)$</th>
<th>$J_k(v_k)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$\Delta v$</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$2\Delta v$</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>.</td>
<td>.</td>
<td>.</td>
</tr>
<tr>
<td>.</td>
<td>.</td>
<td>.</td>
</tr>
<tr>
<td>$I_k\Delta v$</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Having completed the least costs and best paths for stage $N-2$, the table for stage $N-1$ can
be discarded since in determining costs at stage $N-3$, only the costs from the previous
stage, $N-2$, to the final state are needed. But the best path information must be retained.

The least-cost paths from all possible states at stage $N-3$ to state $v_N$ can be similarly found,
and so on with the remaining stages. When the least-cost path for the last stage $k = 0$ is
obtained, the optimal solution can be retrieved from the best-path information stored during
the backward programming process.
known: $t_0$, $v_0$, $t_N$, $v_N$
chosen: $\Delta x$, $\Delta v$

$\alpha_N(v_N) = 0$, $J_N(v_N) = 0$

$k = N - 1$

$v_i = \Delta v$

$J_k(v_i) = \infty$

$v_j = \Delta v$

$v_j$ a possible state at stage $k+1$?

Yes

$v_i$ to $v_j$ possible?

Yes

$\alpha = c_k + J_{k+1}(v_j)$

$\alpha < J_k(v_i)$?

Yes

$J_k(v_i) = \alpha$

$\alpha_k(v_i) = a$

$\text{path}_k(v_i) = v_j$

$v_j = v_j + \Delta v$

$\text{Yes}$

$v_j > \overline{v}_{k+1}$

Yes

$v_i = v_i + \Delta v$

$\text{No}$

$v_j > \overline{v}_k$

Yes

$\text{No}$

No

No

No

Figure C.2 Flow Chart of Dynamic Programming For Solving the Optimal Speed Profile. The heavily framed block is decomposed in Figure C.3. The $\infty$ represents a large positive number.
Figure C.2 (Cont'd) Flow Chart of Dynamic Programming For Solving the Optimal Speed Profile.
Figure C.3 Flow Chart of Testing if it is Possible to Reach $v_j$ at stage $k+1$ From $v_i$ at Stage $k$. 
APPENDIX D

RESULTS SUMMARY AND DISCUSSION
OF THE PRELIMINARY EXPERIMENT

D.1 SUBJECTIVE RATING ON WORKLOAD

After each test run, subjects were asked to rate the workload in terms of time pressure, mental effort and stress level for the run, with 1—small, 2—medium, or 3—large workload. Definitions of these scales were explicitly explained in the questionnaire. The root-mean-square of the three measures, named SWAT (Subjective Workload Assessment Technique) scale, was used to compare workload across test conditions. The overall difficulty of the test run was also measured by subjects' post-test rating on a scale from 1 to 5, progressing from simple to impossible. Results, shown in Figures D.1 and D.2, strongly indicate that the preview relieved subjects' workload. In particular, there was a strong trend of reduction in workload rating for the preview case ($p = 0.069$). Ratings of workload were significantly lower before preview failure than after the failure ($p < 0.01$). Preview also significantly affected the subjects' rating on overall difficulty associated with using the displays ($\bar{X} = 3.5$ with the basic display vs. $\bar{X} = 1.9$ with the preview display on a scale from 1 to 5). In addition, all subjects preferred the preview display to the basic for performing the driving task.

![Figure D.1 Measure of Workload in SWAT scale.](image-url)
Appendix D Results Summary and Discussion of The Preliminary Experiment

D.2 SITUATION AWARENESS

Each answer to the temporary-freeze queries was compared to actual values, as collected by the simulation computer at the time of freeze (at the fixed location). The questions asked subjects to identify the current trip leg, current acceleration state, speed limit of the current block, and speed limit of the next block. The error percentage of total data points was calculated on each query item (scored either right or wrong).

It was surprising that in spite of its being the most important among the query items, the speed limit of the next block had the highest error rate (67% with basic, 50% with preview, 42% with preview failure). This suggests that subjects, in general, had low situation awareness in all three test conditions.

However, a conclusion from this measure alone may be premature, especially considering the small number of data points (12 for the test with failure, 6 for the others). In fact, a qualitative evaluation of subjects’ individual responses (speed profiles) reveals that some subjects (8 out of 12) started braking for upcoming speed reductions earlier with the previews than with the basic. This evidence indicates that preview improved situation awareness. That subjects lacked training for this experiment, as evidenced in several accounts discussed in Section D.8, may explain the surprising results from the query method.

Figure D.2 Overall Difficulty.
D.3 SPEED COMPLIANCE

The total number of speed infractions committed as a result of late braking for upcoming speed reductions was recorded. Subjects had fewer incidents of excessive speed violation (exceeding speed limit more than 15 km/h) with the preview than with the basic display (8 for runs with preview, 13 with the basic display, 6 before the failure, and 11 after the failure). These results show that preview seemed to have increased subject's awareness of the upcoming situation and reduced the error of braking too late by increasing awareness of the speed restrictions ahead. Therefore, preview showed the potential of increasing safety.

The relatively large number of speed violations across all test conditions could be attributed to subjects' lack of training on or knowledge of the train's dynamics. Although, with the preview display, they tended to start braking earlier than with the basic display, underestimation of the braking distance could be the major cause of the subjects' delay in braking.

D.4 SCHEDULE ADHERENCE

Preview appeared to reduce schedule deviation, the difference between scheduled and actual arrival times. Results show that, with the preview display, subjects generally maintained the schedule with an average delay of about 1 minute at 100 km into the journey. In contrast, after 100 km with the basic display, subjects accumulated an average delay of more than 6 minutes.

D.5 STATION-STOPPING ACCURACY

Station-stopping accuracy was evaluated using the absolute distance between the station point and the first point at which the train was manually stopped (ignoring stoppings by inching close to the station after a failure of the first attempt). Among the 36 data points for station stopping, 97% stopped within 20 m of the station with the preview display ($\bar{X} = 1.6$ m) versus 72% with the basic display ($\bar{X} = 2.3$ m). This result shows that the indicator of minimum stopping distance in the preview display tends to improve station-stopping accuracy. The results, however, may be biased by the simulation environment. With the preview display, subjects had two indicators for station stopping: the indicator of the minimum stopping distance and the numerical display of the distance to the next station; with the basic display, only the latter was available. With an out-the-window view, the
subjects would have had other visual cues to guide them during station stopping, and the poor performance in station stopping without the preview might not be so evident.

D.6 OTHER MEASURES

Response to Alert System. In addition to the performance measures summarized above, the time that elapsed before the subject acknowledged an alert system warning was also recorded. All subjects responded to alert warnings on time. None neglected the warning in any test run.

Passenger Ride Quality. Ride quality did not show improvement with the preview display. This was expected since the jerky motion caused by driver's throttle manipulation is primarily associated with driving style (assuming subjects were not overloaded). If a subject is inclined to bang-bang control, unless a specific measure of ride-quality is displayed to the subject during the run or subjects are trained to manipulate the throttle smoothly, no improvement in ride quality can be expected with any display.

D.7 LESSONS LEARNED

Several pieces of evidence suggest that subjects lacked training for this experiment. First, ride quality was not stressed enough; subjects had no idea of how large the jerk was when applying sudden braking or traction (since the simulator was fixed-base). Second, some subjects did not fully understand the implications of speed reduction ahead to their current speed control, or the relative importance of an increase in speed limit to that of a decrease. In addition, there were subjects who did not understand terms that appeared in the questionnaire, e.g. "block". Third, although the preview helped subjects reduce occurrences of speed violation, the high rate of automatic penalty emergency braking across all test conditions suggests that subjects lacked experience with the train dynamics. As pointed out earlier, subjects started braking earlier with the preview than with the basic display for upcoming speed limit reductions. However, the braking was often not initiated early enough to avoid excessive overspeeding, which indicates that subjects underestimated the braking distance required from the current speed to the upcoming lower speed limit.
The experience of this experiment contributed to subsequent studies in the following aspects of experimental design:

1. Screen subjects with a qualifying test. After all, not all people bring along the same capability to become a locomotive engineer. Each subject should be given a fixed amount of training followed by a standardized qualifying examination.

2. Train subjects to improve passenger ride quality by providing feedback during training. Such feedback should help subjects adopt a sensitive driving style and improve passenger ride quality.

3. Ensure subjects' thorough understanding of the importance and functionality of all items on the display.
APPENDIX E

GUIDE TO OPTIMAL THROTTLE MANIPULATION

<table>
<thead>
<tr>
<th>Enroute</th>
<th>Action</th>
<th>Location (KP*)/when</th>
<th>Speed (km/h)</th>
<th>Landmark</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accelerate (100% gradual reduction to 94% propulsion)</td>
<td>0</td>
<td>0</td>
<td>NYC station</td>
<td></td>
</tr>
<tr>
<td>Cruise (34–38% propulsion)</td>
<td>9</td>
<td>240</td>
<td>Christmas trees</td>
<td></td>
</tr>
<tr>
<td>Accelerate (~90% propulsion)</td>
<td>14</td>
<td>240</td>
<td>Twin blue towers</td>
<td></td>
</tr>
<tr>
<td>Coast (throttle neutral)</td>
<td>17</td>
<td>~259</td>
<td>Red overhead bridge</td>
<td></td>
</tr>
<tr>
<td>Coast/Small braking (~2%)</td>
<td>19</td>
<td></td>
<td>Red ancient gate</td>
<td></td>
</tr>
<tr>
<td>Large braking (90–100%)</td>
<td>23.2</td>
<td>222</td>
<td>Twin blue tilted towers</td>
<td></td>
</tr>
<tr>
<td>Cruise (~4% propulsion)</td>
<td>28</td>
<td>70</td>
<td>Red China gate</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(~800m to station)</td>
<td></td>
<td>Head-up display shows up</td>
<td></td>
</tr>
</tbody>
</table>

Approach Station With The Basic Display

<table>
<thead>
<tr>
<th>Approach station</th>
<th>(~600m to station)</th>
<th>70</th>
<th>Out-the-window view—4th set of tunnel lights crosses head-up display</th>
</tr>
</thead>
<tbody>
<tr>
<td>Check and adjust</td>
<td>~60</td>
<td>3rd set of lights...</td>
<td></td>
</tr>
<tr>
<td>Check and adjust</td>
<td>~50</td>
<td>2nd set of lights...</td>
<td></td>
</tr>
<tr>
<td>Check and adjust</td>
<td>~40</td>
<td>Station wall...</td>
<td></td>
</tr>
<tr>
<td>Check and adjust</td>
<td>~18</td>
<td>Top of station signal sign...</td>
<td></td>
</tr>
<tr>
<td>Reduce braking to ~25% to avoid jerky stop</td>
<td>Just before train stops</td>
<td>2~1</td>
<td></td>
</tr>
</tbody>
</table>

* KP—kilometer post
APPENDIX F

TABLE OF STOPPING DISTANCE

<table>
<thead>
<tr>
<th>Speed (km/h)</th>
<th>Stopping distance — full-service (km)</th>
<th>Stopping distance — emergency (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>300</td>
<td>8.390</td>
<td>2.704</td>
</tr>
<tr>
<td>240</td>
<td>5.684</td>
<td>1.765</td>
</tr>
<tr>
<td>80</td>
<td>0.706</td>
<td>0.201</td>
</tr>
<tr>
<td>70</td>
<td>0.534</td>
<td>0.153</td>
</tr>
<tr>
<td>60</td>
<td>0.400</td>
<td>0.114</td>
</tr>
<tr>
<td>30</td>
<td>0.101</td>
<td>0.028</td>
</tr>
<tr>
<td>20</td>
<td>0.045</td>
<td>0.012</td>
</tr>
<tr>
<td>10</td>
<td>0.011</td>
<td>0.001</td>
</tr>
</tbody>
</table>
APPENDIX G

SPEED-STOPPING DISTANCE CURVE

- Speed (km/h)
- Stopping Distance (km)

- ■ Emergency Stop
- □ Full Service
**APPENDIX H**

**INCENTIVE SYSTEM**

---

**Bonus Comparison Table**

(For Routine Speed Control)

<table>
<thead>
<tr>
<th>Performance</th>
<th>5</th>
<th>4</th>
<th>3</th>
<th>2</th>
<th>1</th>
<th>0</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Station Overshoot</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Station Undershoot</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>[meters]</td>
<td>0 ~ 2</td>
<td>2 ~ 3</td>
<td>3 ~ 4</td>
<td>4 ~ 5</td>
<td>5 ~ 6</td>
<td>≥ 6</td>
</tr>
<tr>
<td></td>
<td>0 ~ 2</td>
<td>2 ~ 4</td>
<td>4 ~ 6</td>
<td>6 ~ 8</td>
<td>8 ~ 10</td>
<td>≥ 10</td>
</tr>
<tr>
<td><strong>Arrival Late</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Arrival Early</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>[seconds]</td>
<td>0 ~ 8</td>
<td>8 ~ 12</td>
<td>12 ~ 16</td>
<td>16 ~ 20</td>
<td>20 ~ 24</td>
<td>24 ~ 60*</td>
</tr>
<tr>
<td></td>
<td>0 ~ 10</td>
<td>10 ~ 14</td>
<td>14 ~ 18</td>
<td>18 ~ 22</td>
<td>22 ~ 26</td>
<td>≥ 26</td>
</tr>
<tr>
<td><strong>Distance Oversped</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>[meters]</td>
<td>0</td>
<td>0 ~ 70</td>
<td>50 ~ 144</td>
<td>144 ~ 210</td>
<td>210 ~ 280</td>
<td>≥ 280</td>
</tr>
<tr>
<td><strong>Large Jerks</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>[times]</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>≥ 5</td>
</tr>
<tr>
<td><strong>Energy</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>[% optimal energy]</td>
<td>0 ~ 20</td>
<td>20 ~ 30</td>
<td>30 ~ 40</td>
<td>40 ~ 50</td>
<td>50 ~ 60</td>
<td>≥ 60</td>
</tr>
</tbody>
</table>

* A negative bonus point is given for delay of every additional 10 seconds after an initial delay of 60 seconds.
Additional Bonus

(For Runs of Speed Control with Secondary Task)

At best: 10% of the bonus earned on routine speed control

At worst: Loss of all bonus points earned on routine speed control.

In general, points are awarded according to the schedule shown in Figure H.1.

![Graph showing the relationship between average tracking error and percentage of bonus on speed control.]

Figure H.1 Additional Bonus On the Secondary Task.
The additional bonus was awarded as a percentage of the bonus earned on the routine speed control.
Bonus System
(For Runs with Emergency Situations)

If reaction is fast and a proper control decision is made during the emergency situation, 25 bonus points are awarded. Otherwise, the following rules apply (refer to table H.1):

- If emergency braking is used to avoid a red-light overrun, between 10 and 20 points are awarded depending on the distance from the stop point of the train to the red lights. The closer the train to the red lights, the more points that are awarded.

- If a red-light overrun is committed, negative points are given depending on the speed at the moment of the red-light overrun. The higher the speed, the more the negative points.

<table>
<thead>
<tr>
<th>Outcome</th>
<th>Bonus Points</th>
</tr>
</thead>
<tbody>
<tr>
<td>Safe Stop With Full-Service Braking</td>
<td>25</td>
</tr>
<tr>
<td>Safe Stop With Emergency Braking</td>
<td>10 + 10(1 - (\frac{\text{distance to red lights at stop}}{\text{maximum possible distance to red lights at stop}}))</td>
</tr>
<tr>
<td>Red-Light Overrun</td>
<td>-10x speed at red-light overrun (km/h)</td>
</tr>
</tbody>
</table>
APPENDIX I

SUBJECT CONSENT FORM

The U. S. Department of Health and Human Services requires that all persons used as subjects in experiments sign a consent agreement.

The procedures to be followed involve you making observations from computer or related displays, making decisions, and communicating these by mechanical or verbal means to be provided and explained to you in detail. These experiments do not, in our judgment, pose any risks or hazards to your health or well-being. You are free to ask questions and have them answered to your satisfaction, and are free to withdraw consent and discontinue participating at any time without prejudice.

I understand that I may contact the Chairman of the Committee on the Use of Humans as Experimental Subjects, MIT 253-6787, if I feel I have been treated unfairly as a subject, and that further information may be obtained by calling the MIT Insurance and Legal Affairs Office at 253-2822.

I consent to be a subject in the MIT Human-Machine Systems Laboratory under the above stated conditions.

_________________________  _________________________
(signature)                (date)
APPENDIX J

In-Class Excercises

The instructor did the following three examples in the next page together with the subject during the first session of training, Instructions and Demonstrations.

Figures in the next page show three possible speed limit-signal situations that the subject might encounter at the entrance to certain blocks along a track. The track, which has identical 2-km blocks, is sketched for convenience. The speedometer in these figures indicates the speed limit of the current block (thin line across the width of the speedometer), speed limit of the next block (thick line about one third of the width of the speedometer), and current speed of the train (the thin line right adjusted to the speedometer).

The task is to fill in the effective speed limits asked for under each figure and, in addition, explain what action the ATP (automatic train protection) system would take (does nothing, beeps and flashes yellow, activates the emergency stop and turns red, etc.) if it functions properly.
Appendix J In-Class Exercises

Example 1

Just entered Block 1

Current block ________ (km/h)
Next block ________ (km/h)
ATP ________

Example 2

Just entered Block 1

Current block ________ (km/h)
Next block ________ (km/h)
4 km ahead ________ (km/h)
6 km ahead ________ (km/h)
10 km ahead ________ (km/h)
ATP ________

Example 3

Just entered Block 6

Current block ________ (km/h)
Next block ________ (km/h)
4 km ahead ________ (km/h)
6 km ahead ________ (km/h)
ATP ________
APPENDIX K

TEST FOR ENTRANCE TO HANDS-ON TRAINING ON HIGH-SPEED TRAIN SIMULATOR

This test is designed to evaluate your in-class understanding of the basic rules, train dynamics and other concepts associated with using the high-speed train simulator in the Volpe National Transportation Systems Center. All questions are within the scope of today’s lecture.

The test is to be completed in 30 minutes.
1. Figure 1 shows a stretch of straight and flat track 30 kilometers long. All blocks are of equal length and block numbers are marked along the track. **Please answer the following questions:**

(a) What is the block length (in kilometers)? __________

(b) Why is the set of signal speeds 300, 270, 220, 160, 80, and 0 (km/h) chosen for an interlocking system of 2-km block length?

(c) In Figure 1, please sketch the civil speed limit profile for this track given the following specifications:

<table>
<thead>
<tr>
<th>Block #</th>
<th>0</th>
<th>1</th>
<th>2–6</th>
<th>7–10</th>
<th>11</th>
<th>12</th>
<th>13</th>
<th>14</th>
</tr>
</thead>
<tbody>
<tr>
<td>Speed limit (km/h)</td>
<td>150</td>
<td>200</td>
<td>250</td>
<td>300</td>
<td>270</td>
<td>220</td>
<td>160</td>
<td>80</td>
</tr>
</tbody>
</table>

(d) Assuming block 13 is occupied by a train or an object, please sketch the new effective speed limits on the track and mark the signal aspects above the effective speed limits for all blocks on the track in abbreviated forms (corresponding to the color coding of the signal aspects, e.g. YRY for yellow-red-yellow aspect)
2. Figures 2.a - 2.d show four possible speed profiles on the same track. Which one is the most desirable or the closest to the optimal speed profile based on what you saw during the demonstration?

![Figure 2.a](image)

![Figure 2.b](image)
Figure 2.c

Figure 2.d
3. **Fill in the blanks.**

(a) The ratio between the emergency stopping distance and the full-service stopping distance is approximately _________.

(b) At block boundaries, always monitor the _________________.

(c) In case of an unexpected situation (obstruction), your first reaction should be ________________, and then decide if ________________ is needed.

(d) When an obstruction is shorter than your emergency stopping distance, use emergency stop as ___________ as possible.

(e) When you think you will have to use emergency stop to avoid an obstacle or hitting the front train, use it as ___________ as possible. However, never trade using emergency stop for a collision with the obstruction.

(e) You should operate the train at approximately __________ under the speed limit.

4. **You will lose bonus points under the following situations (choose all that apply):**

(a) If the automatic train protection system warns about overspeeding by blinking yellow with beeps, even if emergency stop is not activated.

(b) If large jerks are created by abrupt throttle manipulation.

(c) If you are more than 60 seconds late to arrive at the station (in fact, you will start earning negative bonus).

(d) If emergency stop is activated out of careless speed control.

(e) If you hit an object or enter the RRR-signaled block due to your poor decision (in fact, you will receive negative bonus points).
Appendix K  Test for Entrance to Hands-on Training on High-Speed Train Simulator

5. Figures 5.1 - 5.3 show three possible speed limit/signal situations that you might encounter at the entrance to certain blocks along a track. The track, which has identical 2-km blocks, is sketched in Figure 5.4. The speedometer in the next block (thick line about one third of the width of the speedometer), speed limit line right adjusted to the speedometer).

Please fill in the effective speed limits asked under each figure. In addition, explain what action the ATP (Automatic Train Protection) system would take if the ATP functions properly (does nothing, beeps and flashes yellow, activates the emergency stop and turns red, etc.).
6. Please answer the following questions. A rough estimate is enough.

(a) What is the stopping distances when the speed of the train is

- 280 km/h? Full service braking: __________ (km) which is about __________ blocks
  Emergency stop: __________ (km) which is about __________ blocks

- 240 km/h? Full service braking: __________ (km) which is about __________ blocks
  Emergency stop: __________ (km) which is about __________ blocks

- 80 km/h? Full service braking: __________ (km) which is about __________ blocks
  Emergency stop: __________ (km) which is about __________ blocks
6. (b) Assume that the ATP (automatic train protection) system has failed and you encounter the following situations. **What should be your responses?** Choose one answer.

(a) Full-service braking only.  
(b) Full-service braking, then, emergency stop when speed is lower.  
(c) Emergency stop immediately.

(a) Full-service braking only.  
(b) Full-service braking, then, emergency stop when speed is lower.  
(c) Emergency stop immediately.

(a) Full-service braking only.  
(b) Full-service braking, then, emergency stop when speed is lower.  
(c) Emergency stop immediately.

(a) Full-service braking only.  
(b) Full-service braking, then, emergency stop when speed is lower.  
(c) Emergency stop immediately.
7. (a) Figure 7.a is a sketch of the Basic display. Answer the following questions about the Basic display:

(1) How far are you from the departing station if the trip leg is 30 km long? ________
(2) Which kilometer post are you at? ________
(3) How far are you from the next station if the trip leg is 30 km long? ________
(4) Which block are you at? ________
(5) What are the effective speed limits of the current and the next blocks? ________ (km/h) and ________ (km/h)
(6) What's the current time? ________
(7) What is the control force state, applying tractive effort (or thrusting force) or braking? ________________
   How much is it as compared to the maximum available force or braking? ________
(8) What is the grade of your current location? ________
Appendix K Test for Entrance to Hands-on Training on High-Speed Train Simulator

7. (b) Answer the following questions or fill in blanks based on the Preview Predictor display shown below.

(1) What is the difference between the Preview-Predictor and the Preview-Predictor-Advisor displays?

(2) What would be the train's speed 20 seconds later if the current throttle braking remains unchanged?

(3) How fast is the train this moment?

(4) Approximately, how long is the full-service stopping distance at the current speed?

(5) The effective speed limit at block 6 at this moment is _____________.

(6) The destination of the trip is _____________.

(7) When might you need to use emergency stop? How would you use the emergency braking curve to help you making speed-control decisions?
APPENDIX L

Test for Entrance to Experiments on High-Speed Train Simulator

This test is designed to evaluate your familiarity with the landmarks around the route, your understanding of the in-cab displays, and your grasp of the train dynamics and driving techniques. This test is taken following the hands-on training as part of the training program. You must pass this exam to proceed to the experimental tests. All questions are within the scope of today’s training session.

The test is to be completed in 5 minutes.
1. (a) Sketch, on Figure 1, the civil limit speed profile of the track you have been driving on.

(b) What are the landmarks for Block 7 and Block 14?

(c) How far is it to Boston when the yellow rectangular marker is shown on your windshield?

(d) What and where are the landmarks as cues for the following throttle manipulations in order to produce an optimal trajectory:

1. start **cruising** at around 240 km/h
2. start **accelerating** with about 90% of tractive effort after the above cruising at 240 km/h
3. start **coasting** (throttle at neutral)
4. apply **small braking** (about 2% of full-service braking)
5. apply **large braking** (about 90% of full-service braking)
6. start **cruising** at 70 km/h
7. **approach station** with 90% – 100% full service braking

Figure 1
2. Sketch, on Figure 2, the approximate speed-stopping distance curves for both full-service and emergency brakings for the train that you have been driving. Label both lines. You should first mark the points for speeds of 70, 240, and 300 km/h, and then use these points as guides to sketch the curves.
3. Fill in the blanks.

(a) The ______________ (an onboard safety system) requests acknowledgment at a random cycle. You should reset it by pressing the __________ key.

(b) When emergency braking has been activated by the automatic train protection (ATP) system (hope it never happens), you should press the ______ key to reset the ATP system before restarting the train.

(c) List all the signal color codes and their corresponding signal speeds.

| __   __   __ | __   __   __ |
| __   __   __ | __   __   __ |
| __   __   __ | __   __   __ |
| __   __   __ | __   __   __ |
| __   __   __ | __   __   __ |
| __   __   __ | __   __   __ |
| __   __   __ | __   __   __ |

(d) Each block in the test track is __________ long.

(e) The scheduled departure time from the origin is __:__:__, and the arrival time for the destination is __:__:__.

(f) Where are the landmarks generally located along the track? Name the ones that you think are important?

(g) How could you use these landmarks when using the Basic display?

(h) When using the Preview-Predictor or the Preview-Predictor-Advisor displays, the ______ and ______ keys can be used to see closer, which are especially useful when approaching the station.

(i) When using the ______________ display, you should try to follow the ______________ as close as possible.
The analysis of the subjects' performance during training addresses two issues: (1) whether the aided displays reduced driver training time, and (2) whether and in what performance measures subjects had experienced learning. The results could provide insight on using the aided displays as tools for driver training as well as for onboard decision aids.

For speed compliance, the aided displays showed their superiority over the basic display. No subjects ever committed a speed violation with the aided displays during training. In contrast, with the basic display, there were 2 incidents of speed violation during the first practice, 2 for the second, and 1 for the third. The trend of reduced distance of overspeeding (Figure M.1) indicates that with the basic display subjects improved in speed compliance during the training. With the aided displays, in contrast, no overspeeding was committed by any subject in any practice run. This result implies that the aided displays had an inherent tendency for better speed compliance than the basic display.

Ride quality, as measured by the number of jerks, was clearly and expectedly improved over the course of training for all displays. By the third run with each display, the total number of jerks was reduced to at least half of that in the first runs of the corresponding displays. This result indicates that the assumption that subjects were well-trained with train-handling was well supported; therefore, it was not necessary for the Jerkometer to be shown during the testing. The successful reduction in jerks through training also demonstrates that the Jerkometer created for the training purpose, was effective.

As for energy consumption, schedule adherence, and station-stopping accuracy, the data in Figure M.1 show no perceivable trend or pattern of learning over the three consecutive runs with each display. The difference was evident across displays rather than across practice runs within each display. This implies that the use of the advisor display would reduce cost regardless of subjects' experience. Similarly, the three practices with each display during the training did not seem to affect station-stopping and schedule adherence within each display.
That no learning was evident may be explained as follows. Subjects were trained by the researcher (the author) under intensive coaching throughout the training sessions. The subjects' learning was, therefore, confounded with the level of coaching. As the practices progressed, the subjects were given less coaching. In fact, at the third practice run with each display, the researcher kept the amount of coaching to a minimum level because (1) the subjects were observed to be able to independently perform the task satisfactorily, and (2) the performance in the third runs was to be assessed as the "road evaluation" for their qualification for the experimental tests.

In summary, the aided displays appear to allow a novice better performance in speed compliance, energy consumption, schedule adherence, and station-stopping accuracy than the basic display. This implies that a much shorter time would be needed to train a novice to a given level of performance with the aided displays than with the basic display. With aiding, no speed violation occurred on any training run; without aiding, subjects achieved low speed violation (total of 15 meters) only after a full set of training runs. Passenger ride quality improved with training for all displays. The learning was actually stronger than that shown in Figure M.1 because the training was confounded with the researcher's coaching, the amount of which was reduced as the number of practice run increased. In fact, without such learning—reduced need for coaching—subjects would not have been able to pass the "road evaluation" conducted during the training. The reduced need for coaching as the training progresses indicated subjects' readiness for experimental tests. Such evidence of readiness adds confidence to the experimental results discussed in this thesis.
Figure M.1 Performance During Training (Continued on next page).
Figure M.1  Performance During Training (Cont'd).
APPENDIX N

SUBJECTIVE WORKLOAD ASSESSMENT (I)

The following questions are to be completed immediately after each test run.

1) How would you rate the time pressures of this test run? In other words, how did the time available relate to the work that needed to be done? Please circle the value that best describes your rating of the time pressures in the following scale.

<table>
<thead>
<tr>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>plenty of spare time, no overlap of activities.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>almost no spare time, very frequent overlap of activities.</td>
</tr>
</tbody>
</table>

2) How would you rate the mental effort required to perform this test run? In other words, what was the level of thinking required? Please circle the value that best describes your rating of the mental effort in the following scale.

<table>
<thead>
<tr>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>very little concentration required, activities are almost automatic.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>high concentration required, highly complex activities.</td>
</tr>
</tbody>
</table>

3) How would you rate the stress caused by this test run? Please circle the value that best describes your rating of the stress in the following scale.

<table>
<thead>
<tr>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>low stress, very little confusion or frustration.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>high stress, high determination and self-control required.</td>
</tr>
</tbody>
</table>
APPENDIX O

SUBJECTIVE WORKLOAD ASSESSMENT (II)

The following questions are to be completed after all test runs.

1) If the overall workload for test runs with the basic display is assigned 100, please rate the overall workload for test runs with the predictor display and the overall workload for test runs with advisor display. Note that a rating value larger than 100 means higher workload than that for all test runs with the basic display. Correspondingly, a rating value smaller than 100 means lower workload than that for all test runs with the basic display.

If the workload for the basic display is assigned 100, I would rate the workload for the predictor display ____________, and rate the advisor display ____________.

2) Which display do you prefer the most, the basic, the predictor, or the advisor?

Why?

3) Which display do you most dislike, the basic, the predictor, or the advisor?

Why?
P. 1 CONSIDERATION OF FUNCTIONAL COMPONENTS

The structure of the rule-based driver model is described with hierarchical functional block diagrams. The functional components that have lower level decomposition are highlighted with heavy frames in each block diagram. Each decomposition diagram has the same title as the name of the corresponding function at the level above. Figure P.1 shows the top level block diagram of the driver model.

Figure P.1 Driver Model (top level).
Perception

First it should be noted that the out-of-window view is not explicitly shown as a source of information to the driver in Figure P.1. The model recognizes the use of an outside view as mainly for cues (landmarks) associated with control maneuvers, and therefore the function of the outside view to the driver has been considered as part of the knowledge base of route characteristics.

An important question in developing such a model is what the driver perceives from a given indicator. For a numerical (digital) indicator such as that of the current speed, it is assumed that perception is just a read of the value of the indicator. The same can be assumed for a graphical discrete display of a variable such as the signal level of a block. Under this assumption, perception of all indicators in the basic display can be modeled as direct reading of the values of the indicators.

A different treatment is needed, however, for modeling perception of a continuous range of graphically displayed information. In this case, perception is assumed to be a process of extracting only the pieces of information useful for current decision making. For example, for the previewed speed limit profile in the predictor display, it is assumed that the driver extracts the location and the level of speed reduction in the preview range (the subjects were in fact trained to use the aid in such a manner), as illustrated in Figure P.2. The rationale behind this assumption is that it is the speed reductions that need the driver’s advance attention so that braking can be initiated in time to reduce the train’s speed to the speed limit of the next block before reaching that block. Therefore, pairs of speed reduction and distance to speed reduction are extracted from the profiles of the speed limit and the signal in the preview range.

The pairs of location and level of speed reduction will be used, in turn, by the driver to derive needed information from the full-service braking curve, also illustrated in Figure P.2. The braking distances from the current speed to the reduced speed levels in the preview range, i.e., the $V_{\text{reduction}}$’s (Figure P.2), are then extracted from the full-service braking curve. Thus, the decision as to whether braking is needed at any moment can be reached by comparing the braking distances and the distances to the points of corresponding speed reductions, i.e., the $x_{\text{reduction}}$’s (Figure P.2). Therefore, only crucial data or pieces of information are extracted by the driver from the full-service braking curve during the perception process.
Appendix P Implementation of Simulation Driver Model

The block diagram of perception, together with other block diagrams describing rules implemented in the model, is shown in Figures P.3-P.12.

![Diagram of speed limit profile and predictor curves]

Figure P.2 Extraction of Relevant Information From Speed Limit Profile and Predictor Curves. Only locations and corresponding levels of speed reductions are extracted from the previewed speed limit profile. Corresponding pieces of information from the predictor curves are also extracted as needed.

Knowledge Base

The knowledge base combined with the control decision rules contains all the information and knowledge a driver has at his disposal in the form of charts, route maps, experience gained, and rules or procedures learned during training and previous journeys. Each of the four functional components of the knowledge base shown in Figure P.1 has its own role in decision making. The train dynamic characteristics are crucial for estimating the moment or location to start braking to bring the speed of the train below the speed limit a certain distance away. The train-handling technique reflects the driver's skill at throttle manipulation under the constraint of ride quality. The route characteristics is needed to recognize the station or major "points of no return." The schedule is used to compensate for schedule deviation. Functions of these knowledge components are manifest in the decision rules discussed next.
Schedule Adjustment

The rule for schedule adjustment, shown in Figure P.12, needs some explanation. If on schedule (i.e., behind by less than 8 sec or ahead by less than 10 sec), the speed at which the train should cruise (when necessary) shall be 10 km/h under the speed limit; if late, this speed should be 5 km/h under the speed limit; if early, 15 km/h. These adjustments only affect the speed when train is cruising; if no segment of the trip requires cruising, this method of schedule adjustment has no effect on schedule adherence. Therefore, the schedule compensation implemented in the model is limited in its capability by speed limit constraints.

Preservation of Ride Quality

Just the moment before the train stops, the braking force should be reduced to a level below 30% of the full-service braking to preserve good ride quality. A 28% full-service braking was implemented in the model, as shown in Figures P.4 and P.9.

P.2 IMPLEMENTATION ASPECTS

The model was implemented as part of the high-speed train simulator developed for the Volpe National Transportation Systems Center on Silicon Graphics workstations in the C programming language. The model is capable of fast-time simulation and with a provision for real-time simulation. The implementation of the model is flexible because signal events can be flexibly configured and tested with different command-line input parameters, and all parameters can be easily varied including those of driver limitations in detection of signals. These features make the model a useful tool for predicting the effect of driver characteristics on performance by suitably varying driver-related parameters of the model.

In order to obtain a simulated response with the model, the following information that describes the knowledge base, performance criteria, and driver limitations must be provided. Because the model is a simulation model, the timing parameter must also be specified. The parameters and functional components for the driver-cab simulation model are summarized in Table P.1.
Table P.1 Inputs to The Driver-Cab Simulation Model

<table>
<thead>
<tr>
<th>Driving Environment</th>
<th>Cab displays (basic, predictor or advisor)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Signal event</td>
</tr>
<tr>
<td>Driver Characteristics</td>
<td>Knowledge of train characteristics (braking/propulsive behavior)</td>
</tr>
<tr>
<td></td>
<td>Knowledge of trip characteristics (schedule, route, points of no returns)</td>
</tr>
<tr>
<td></td>
<td>Train-handling experience (related to ride quality)</td>
</tr>
<tr>
<td></td>
<td>Knowledge of performance criteria and operation rules (e.g., cruise at a speed 10 km/h below the speed limit)</td>
</tr>
<tr>
<td></td>
<td>Knowledge of schedule</td>
</tr>
<tr>
<td></td>
<td>Delay in reaction to signal changes</td>
</tr>
<tr>
<td>Simulation Parameter</td>
<td>Simulation update interval</td>
</tr>
<tr>
<td></td>
<td>Data recording rate</td>
</tr>
</tbody>
</table>

P.3 HIERARCHICAL BLOCK DIAGRAMS

![Hierarchical Block Diagram]

**Figure P.3 Decomposition of Perception.** $V_{\text{reduction}}$—the speed limit in the preview range that is below the current speed of the train. $X_{\text{reduction}}$—the distance from the current location of the train to the $V_{\text{reduction}}$. 

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Figure P.4 Max-Max Control Decision Making. $v$—current speed of the train. $a$—current acceleration of the train.
Figure P.5  Control Decision Making With the Basic Display. \( V_m \)—the margin speed by which amount the train cruises under the speed limit. \( V_{now} \)—speed limit of the current block. \( V_{nxt} \)—speed limit of the next block.

Figure P.6  Control Under Signal Speed Restriction (with the basic display). \( V_m \)—the margin speed by which amount the train cruises under the speed limit. \( V_{nxt} \)—speed limit of the next block.
Appendix P Implementation of Simulation Driver Model

Figure P.7 Control Under Civil Speed Restriction (with the basic display). \( V_m \) — the margin speed by which amount the train cruises under the speed limit. \( V_{\text{now}} \) — speed limit of the current block. \( V_{\text{nxt}} \) — speed limit of the next block. KP — kilometer post.

Figure P.8 Increase Speed to a Given Level \( V_{\text{target}} \). \( V_m \) — the margin speed by which amount the train cruises under the speed limit.
Figure P.9 Cruise at a Given Speed $V_{cruise}$ or Approach Station. $D_{station}$—the distance to the destination station. $D_{stop}$—current stopping distance. $v$—current speed of the train. $a$—current acceleration of the train.
Figure P.10 Decision Making With the Predictor Display. \( V_{\text{now}} \)—speed limit of the current block. \( V_{\text{nxt}} \)—speed limit of the next block. \( V_{\text{reduction}} \)—the speed limit in the preview range that is below the current speed of the train. \( X_{\text{reduction}} \)—the distance from the current location of the train to the \( V_{\text{reduction}} \). KP—kilometer post.
Appendix P Implementation of Simulation Driver Model

Figure P.11 Decrease Speed to a Given Level $V_{\text{target}}$.

Figure P.12 Compensation for Schedule Deviation. $V_m$ — the margin speed by which amount the train cruises under the speed limit.
# Appendix Q

## Individual Data

### Table Q.1 Routine Speed Control (With the Basic Display)

<table>
<thead>
<tr>
<th>Subject</th>
<th>Distance Overspeed (m)</th>
<th>Station Accuracy (m)</th>
<th>Stop Total Cost (m)</th>
<th>Cost Schedule Deviation (sec)</th>
<th>Number of Jerks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>-5.83</td>
<td>22.1706</td>
<td>11.659</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>-1.50</td>
<td>54.0963</td>
<td>27.060</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>13.08</td>
<td>25.0244</td>
<td>-0.663</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>0</td>
<td>11.45</td>
<td>14.0880</td>
<td>6.238</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>0</td>
<td>-3.04</td>
<td>8.4149</td>
<td>0.289</td>
<td>0</td>
</tr>
<tr>
<td>6</td>
<td>0</td>
<td>10.53</td>
<td>19.8035</td>
<td>9.112</td>
<td>0</td>
</tr>
<tr>
<td>7</td>
<td>0</td>
<td>-14.26</td>
<td>9.9647</td>
<td>3.021</td>
<td>0</td>
</tr>
<tr>
<td>8</td>
<td>0</td>
<td>-11.68</td>
<td>7.4584</td>
<td>3.953</td>
<td>0</td>
</tr>
<tr>
<td>9</td>
<td>0</td>
<td>-5.27</td>
<td>40.2291</td>
<td>21.251</td>
<td>0</td>
</tr>
<tr>
<td>10</td>
<td>0</td>
<td>42.72</td>
<td>16.3358</td>
<td>7.730</td>
<td>0</td>
</tr>
<tr>
<td>11</td>
<td>0</td>
<td>31.62</td>
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### Table Q.2 Routine Speed Control (With the Predictor Display)

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<th>Station Accuracy (m)</th>
<th>Stop Total Cost (m)</th>
<th>Cost Schedule Deviation (sec)</th>
<th>Number of Jerks</th>
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### Table Q.3 Routine Speed Control (With the Advisor Display)

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<th>Total Cost (% over optimal)</th>
<th>Schedule Deviation (sec)</th>
<th>Number of Jerks</th>
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<th>Station Stop Accuracy (m)</th>
<th>Total Cost (% over optimal)</th>
<th>Schedule Deviation (sec)</th>
<th>Number of Jerks</th>
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<th>Station Stop Accuracy (m)</th>
<th>Total Cost (% over optimal)</th>
<th>Schedule Deviation (sec)</th>
<th>Number of Jerks</th>
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<th>Total Cost (% over optimal)</th>
<th>Schedule Deviation (sec)</th>
<th>Number of Jerks</th>
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### Table Q.7 Reaction Time (seconds)

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## Table Q.8 Subjective Ratings on Workload (via Immediate-Absolute Method)

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<th>Speed Control With Secondary Task</th>
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* B—the basic display
P—the predictor display
A—the advisor display
### Table Q.9 Subjective Workload Ratings
(via Retrospective-Relative Method)

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### Table Q.10 Subjects' Rankings of the Displays

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Appendix Q Individual Data

Figure Q. 1 Tracking Errors of the Secondary Task by Subjects 1, 2 and 3.
Appendix Q Individual Data

Secondary Task Performance (Subject 4)

Secondary Task Performance (Subject 5)

Secondary Task Performance (Subject 6)

Figure Q. 2 Tracking Errors of the Secondary Task by Subjects 4, 5 and 6.
Figure Q. 3 Tracking Errors of the Secondary Task by Subjects 7, 8 and 9.
Appendix Q Individual Data

Secondary Task Performance (Subject 10)

Figure Q. 4 Tracking Errors of the Secondary Task by Subjects 10, 11 and 12.