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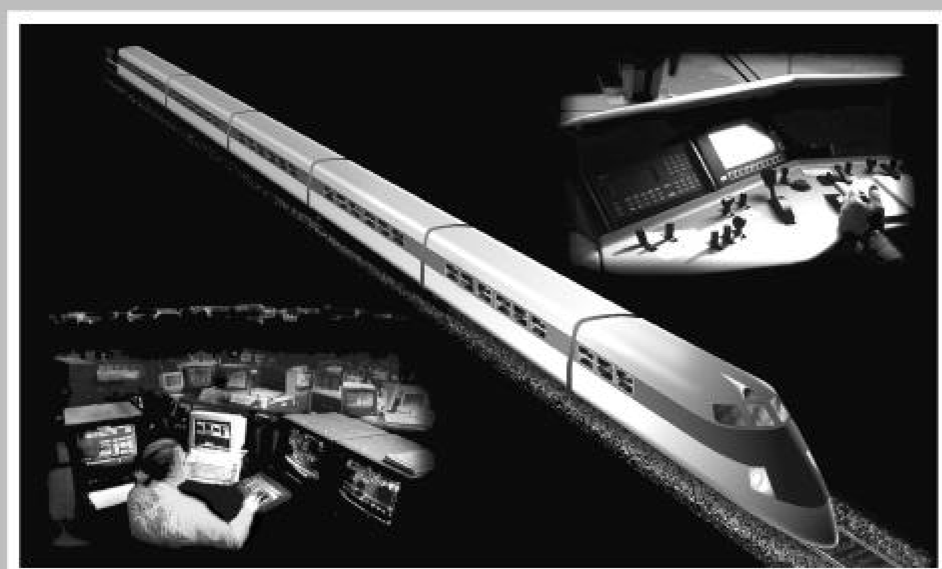
Safety of High-Speed Ground Transportation Systems



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13. ABSTRACT (Maximum 200 words)

Although the speed of some guided ground transportation systems continues to increase, the reaction time and the sensory and information processing capacities of railroad personnel remain constant. This second report in a series examining critical human factors issues in future high-speed rail systems, describes the design and evaluation of computer-based decision aids to compensate for the increased demands on locomotive engineers. (The next report will explore increasing control automation.) Three concepts of aiding, referred to as preview, predictive, and advisory aiding, were integrated into two displays and compared with a conventional high-speed cab environment. Experimental evaluations were conducted on the high-speed-rail simulator developed at the Department of Transportation's Volpe Center for Human Factors Research. Results show that the decision aids improved safety by reducing both reaction times to emergency events and the need for emergency braking. Schedule adherence, station-stopping accuracy, and , with advisory aiding, energy consumption improved. Concerns that aiding may induce higher visual workoad were allayed both empirically and via subjective questionnaires, where the advanced displays were consistently rated lower on workload-related measures. A high-speed train locomotive engineer model was developed to evaluate decision aids in a less costly model-in-the-loop simulation. The findings of the human-in-the-loop evaluation were confirmed.

14. SUBJECT TERMS

Human factors, transportation, high-speed trains, safety, human performance, workload, situation awareness, decision aids, displays, human-in-the-loop simulation, model-in-the-loop simulation

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PREFACE

This work was performed as part of an ongoing research program at the U. S. Department of Transportation's (USDOT's) John A. Volpe National Transportation Systems Center in collaboration with the Human-Machine Systems Laboratory at the Massachusetts Institute of Technology. It is supported by the USDOT's Federal Railroad Administration (FRA) Office of Research and Development as part of its comprehensive effort to develop the technical information necessary for regulating the safety of high-speed guided ground transportation.

As vehicle speed increases, the "speed" of human information processing remains constant. High speed, on the one hand, increases demand on the locomotive engineer's information processing per unit time and, on the other hand, decreases allowable response time. These effects of high speed necessitate a locomotive engineer-cab system that is well "human factored." To this end, the cab and signaling system design has to consider the role of the human. Two approaches to design can be identified to compensate for the discrepancy between vehicle and operator "speed": an increase in automation and the provision of information processing or sensory aids to help operators cope with greater demands.

This report focuses on the human factors issues associated with introducing information processing and sensory aids to the cab while keeping the locomotive engineer fully in control of the vehicle. (A parallel effort investigating the impact of increasing automation on locomotive engineers will be reported separately.)

ACKNOWLEDGMENTS

The authors are deeply grateful to many people who contributed to the completion of this work. We would like to thank Dr. Thomas Raslear of the Federal Railroad Administration, Dr. Donald Sussman, and Mr. Robert Dorer of the Volpe Center for their interest and participation in many discussions, and their support over the course of this research. We very much appreciate the insightful comments from Dr. Raslear on a draft of this report. At Volpe, Mr. J. K. Pollard helped building the throttle that was crucial to the project's progress. Dr. Peter Mengert was readily available to discuss various issues on statistical analysis. Dr. Robert DiSario generously lent us books on experimental design and statistical analysis.

At the Massachusetts Institute of Technology, Mr. Edward Lanzilotta was the co-developer of the simulator which was the major experimental tool used. Dr. Jie Ren built the A/D converter that greatly enhanced the progress of this research. Wendy Chang, Grace Park, Joseph Wenish, and Jill Chen helped testing the simulator and making preparations for the experiments. Professors R. John Hansman and Mark Jakiela were most gracious in being on the first author’s doctoral thesis committee, participating constructive discussions, and providing insightful suggestions. The effort and advice from Professor Hansman were especially valuable.

Mr. John P. Tolman and his colleagues, Mr. George J. Newman and Mr. Walter Nutter, from the Brotherhood of Locomotive Engineers provided valuable inputs during one of our focus group discussions. Mr. Dennis Coffey of the Massachusetts Department of Transportation and Mr. Jack Flaherty of the Massachusetts Bay Transit Association arranged our rides on the front ends. Mr. Stephen Jones and other staff of Amtrak organized our visit to Amtrak's Centralized Electrification and Traffic Control in Boston.

In Japan, Mr. Makoto Shimamura and Mr. Hiroshi Nagaoka arranged the first author’s visit to the East Japan Rail control center in Tokyo and a head-end ride on the Shinkansen.

Finally, we wish to thank Dr. Judith Bürki-Cohen, the project manager at the Volpe Center, for her enthusiasm about this research and her effective guidance and assistance that were invaluable towards the completion of this work.

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ABBREVIATIONS AND TERMINOLOGY†

Alert system	An onboard safety system, also called a "deadman system," that generates a warning at random periods to call for the locomotive engineer's attention. Once the warning is active, a mechanism should be touched or pressed by the locomotive engineer to acknowledge and silence it. The purpose of such an alert system is to monitor whether the locomotive engineer 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.
Box plot	A plot showing the distribution of the data. It consists of a rectangular box with vertical "whiskers" attached to the top and the bottom of the box. The top of the box corresponds to the 75^{th} percentile, and the bottom of the box corresponds to the 25th percentile of the data. The whisker from the top (75^{th} percentile) extends to the maximum, and the whisker from the bottom (25^{th} percentile) extends to the minimum of the

† Rail terminology adapted from (Luedeke, 1992; Sheridan et al., 1994).

data. The bar inside the box is at the 50^{th} percentile, or the median of the data.

Cab	The section of the power car of a trainset where the locomotive engineer works.
Cab signal	A signal located in the engine control compartment or cab indicating a condition affecting the movement of a train or engine and used in connection both with interlocking signals and with, or in lieu of, block signals.
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 a railroad in which a train operating 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).

[††] Item defined by the author.

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 a railroad in which a train operating 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.
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; it may be 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.

[††] Item defined by the author.

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.
Shinkansen††	Japanese high-speed train.
Simulator	A device, computer program, or system that behaves or operates like a given system when provided a set of controlled inputs.
Speed Control	The function of adjusting the instantaneous vehicle speed to a given speed level.
Speed profile††	A plot of speed against distance traveled.
Switch	A pair of switch points with fastenings and operating rods which provides the means for changing a route from one track to another.
TGV	Train à Grande Vitesse (French high-speed train).
Wayside signal	A signal of fixed location along the track right-of-way.

EXECUTIVE SUMMARY

This report describes the design and evaluation of computer-based decision aids to compensate for limits in signal detection and information processing capacity experienced by locomotive engineers of high-speed trains. Three concepts of aiding, referred to as *preview aiding*, *predictive aiding*, and *advisory aiding*, were proposed based on a system analysis of tasks of train operation.

The intent of preview aiding is to compensate for human visual limitations by providing, inside the locomotive cab, necessary information (speed limits, signals, etc.) for a distance spanning farther than the train's longest stopping distance. The preview aiding should be designed to provide not only advance notice of signals but also visual saliency in order to achieve proper attention to relevant information and fast reaction times to unexpected events.

The principle of predictive aiding is to use a computer model to generate more accurate predictions on the consequences of control actions than the human operators could by themselves. This would help them to build a better mental model and improve their manual operation. Therefore, predictive aiding should explicitly display to the locomotive engineer, the future speeds (i.e., instant prediction of the control outcome) in order for the locomotive engineer to take corrective actions much earlier than would be possible otherwise. Two types of predictive aiding were recommended to relieve the locomotive engineer's mental load and aid his or her control decision making. One type answers the question of *what would be the speed profile for the next period of time if the current force application is maintained*; the other type of predictive information answers the question of what *would be the speed profile if either the full-service braking or the emergency braking were quickly applied now*.

The advisory aiding presents a computer-generated optimal speed profile—optimal in terms of total cost (energy consumption plus a weighted schedule deviation) under the constraints of schedule, speed limits, passenger ride quality, and train propulsion and braking capacities. If the human operator kept precisely to such a profile, he or she would have a better speed-control performance than by mentally (and therefore imprecisely) performing the various calculations required for reaching the optimal control decisions.

Natural questions regarding the three proposed concepts of aiding are how to provide the proposed aiding and whether displaying all this aiding would provide too much information and overload the locomotive engineer. To answer these questions, the proposed individual aids were integrated into two displays, each containing different levels of aiding: the *predictor display* contained only the preview and the predictive aiding, and the *advisor display* contained the preview, the predictive and the advisory aiding. A conventional high-speed train cab environment

was also implemented as a baseline for comparison purposes and is referred to as the *basic display*.

The advanced displays were expected to: (1) improve the locomotive engineer's situation awareness because the advance signals provide salient preview and, thus, attract the locomotive engineer's attention and enable anticipation as well as timely response; (2) reduce the locomotive engineer's visual workload—there should be little or no need for the locomotive engineer to intensely scan the fast moving field of view to search for signals or signs since they are displayed inside the cab; (3) reduce the locomotive engineer's reliance on memory of track details—the previewed information on speed limits, track geometry, and so on should help to reduce the locomotive engineer's mental workload of memory retrieval; and (4) reduce mental effort in exercising his or her mental model of the train dynamics and, thus, improve the quality of decision-making on speed control. Unnecessary use of emergency braking would be expected to decrease with the use of the predicted speed profiles (the predictive aiding). Without the predictive aiding, the locomotive engineer would have to estimate the braking distance in order to make a proper judgment as to the use of emergency braking. The advisor display was also expected to reduce the total cost of a trip.

A preliminary and a main experiment were conducted on a distributed interactive high-speed rail simulation which was developed by us at the Center for Transportation Human Factors Research of the Volpe National Transportation Systems Center. The experimental subjects were university students who have the advantage of having equal exposure to all experimental conditions. One disadvantage of using "naive" subjects is the lack of feedback from professional locomotive engineers on the operational validity of the experiments.

Results show that the predictor and the advisor displays were able to increase safety by improving situation awareness as manifested through both the reduction of subjects' mean reaction time to an unexpected signal change from 8.6 seconds to 1.4 seconds and the avoidance of excessive use of emergency braking. Schedule adherence and station-stopping accuracy were found to improve with both advanced displays and the improvements with the advisor display were statistically significant. Ride quality appeared to degrade with the increase in aiding level, which, however, was not found to be statistically significant.

The advisor display reduced total cost (energy consumption plus a weighted schedule-deviation) by up to 11%, the predictor display 5%, with respect to the basic display on a simple experimental track. On real tracks, where the speed limits and track geometry are more varied, the reduction of total cost by the advisor display with respect to the basic display, is expected to be greater than that demonstrated in the main experiment.

To address the concern that increased aiding might induce higher visual workload, several measures of workload and subjects' preference rankings of the displays were obtained. First, although increasing "head-down" time, the advisor display was not found to overload subjects because the spare visual capacities associated with the displays, measured via subjects' performance on a secondary task, were not significantly different across displays. Second, subjective ratings on time pressure, mental effort, and stress for the predictor and the advisor displays were lower than those for the basic display for routine speed control and emergency handling. Third, a retrospective and relative questionnaire revealed a significant decrement of overall workload with the increase in display aiding. Fourth, there was a significant preference for the advanced displays over the basic display: the higher the display level (progressing from the basic to the advisor display), the more it was liked by the subjects.

A high-speed train locomotive engineer model was also developed and applied to evaluate the proposed aiding via model-in-the-loop simulation. The model combined two normative rule-based train control strategies integrated together via a parameter characterizing locomotive engineer behavior in reaction to unexpected signal events. The parameter that described such a behavior was obtained from a human-in-the-loop experiment. As an alternative method of evaluating decision aids proposed for future high-speed trains, a simulation with the model in the loop was conducted under a scenario in which a lead moving train unexpectedly appeared ahead of the model-operated train. The simulation results support the finding of the human-in-the-loop experiment that the proposed aiding is capable of improving safety in terms of speed compliance and reducing energy consumption and schedule delay.

The results of this investigation suggest that the advisor display used in this study (including both preview and predictive aiding) is a promising level of aiding. Although the display tends to shift the locomotive engineer's attention from outside the window to inside the cab, the shift of attention may not be a concern if all important or necessary information is provided inside the cab, especially during high-speed enroute operations.

Before putting the advisor display into service, more research is needed to take advantage of the proposed aids while eliminating any potential negative effects. The divergence between the objective (via secondary task performance) and the subjective measures of workload found in this research, although not significant, shows the importance of such an investigation. For example, different methods of workload measurement may be necessary to obtain further insights on workload associated with the proposed displays. Further, an experiment with professional locomotive engineers would be able to provide more insight on the use of and potential improvement of the proposed aids.

Practical issues associated with implementing the advisor display on a high-speed train include: (1) what on-board computing capability is required to allow updates of the optimal speed profile *en route* (note that the present research was restricted to presenting an optimal profile for the whole trip before departure and without *en route* updates)? (2) how accurate should the "optimal" profile be in order to retain the benefit of cost saving? (3) how should the previewed signals be transmitted into the cab in order to display them in the advanced displays?

As discussed in our earlier report, generally there are two options in aiding the locomotive engineer: more decision aids like those presented in this research, or more automation (Sheridan et al., 1994). Although the direction of this research has been in decision aiding, maybe a combination of the decision aids presented here with some automation could be a better locomotive engineer-cab system design. For example, since station stopping was found to be significantly more demanding of visual attention than *en route* control, it may be worth investigating automated station stopping (e.g., programmed stopping) in connection with the use of the advisor display.

1. INTRODUCTION

The public's desire for faster 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 speed increases, however, the "speed" of human information processing remains constant. High speed affects the human locomotive engineer in two ways: increased demand on the locomotive engineer's information processing per unit time and decreased allowable reaction time. Effects of high speed on demands on the locomotive engineer's information processing are two fold. First, as speed increases, the locomotive engineer is exposed to increasing sensory load because the locomotive engineer must scan the track and its fast-flowing vicinity with increasing intensity to detect signals and dangerous situations. Therefore, high speed increases the difficulty for the locomotive engineer to filter out the relevant information because the same amount of information is being processed in a decreased amount of time. As a result, identification of wayside signals by a locomotive engineer increases in difficulty as speed increases. In practice, 220 km/h is regarded as the maximum speed for correct interpretation of a signal in poor weather (for regular size signals); with falling snow, the speed is naturally lower (Gruère, 1992). Second, the process of information retrieval from the locomotive engineer's memory becomes increasingly intensive. Train operation relies on a continuous retrieval of information of track characteristics, landmarks, the Daily Operating Bulletin (which indicates temporary speed restrictions and the working area of track maintenance crews, among other things), operation rules, and so on. Therefore, as speed increases, the workload of information retrieval from memory increases.

High speed reduces the allowable response time for unexpected dangerous situations, such as sudden appearance of an obstacle because of the train's long stopping distances—at least 4 to 5 kilometers (2.5 to 3.1 miles) for operation at 300 km/h (186 mph) (DOT/FRA, 1991). Hence, accomplishing complete accident prevention and collision avoidance increases in difficulty.

These effects of high speed necessitate a locomotive engineer-cab system that is well "human factored." Two approaches can be identified in designing such locomotive engineer-cab systems. 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 in-cab aids, while keeping the human in control.

Both of the above approaches have potential problems. A major concern associated with increasing automation is possible loss of situation awareness (Endsley and Kiris, 1995). 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 of the information sources and the task at hand. As a result, their performance in signal detection and decision making may deteriorate.

The objectives of this research were (1) to develop computer-based decision aids for control of high-speed trains where the locomotive engineer remains fully in control and (2) to investigate the impacts of these aids on safety and operational efficiency. In particular, this research sought to design and evaluate decision aids to compensate for limits in signal detection and information processing capacity experienced by locomotive engineers of high-speed trains. Under this objective, three concepts of aiding—preview, predictive, and advisory aiding—were proposed.

The idea of preview aiding is to compensate for human visual limitations by providing, inside the locomotive cab, necessary information (speed limits, signals, etc.) for a distance spanning farther than the train's longest stopping distance. The preview aiding should be designed to provide not only advance notice of signals but also visual saliency in order to achieve proper attention to relevant information and fast reaction times to unexpected events.

The principle of predictive aiding is to use a computer model to generate more accurate predictions on the consequences of control actions than the human operators could generate by themselves. This would help them to build a better mental model and anticipate, and improve their manual operation. Therefore, predictive aiding should explicitly display to the locomotive engineer the future speeds (i.e., instant prediction of the control outcome) in order for the locomotive engineer to take corrective actions much earlier than would be possible otherwise. Two types of predictive aiding can be designed to relieve the locomotive engineer's mental load and aid his or her control decision making. One type answers the question of *what would be the speed profile for the next period of time if the current force application is maintained*; the other type of predictive information answers the question of *what would be the speed profile if either the full-service braking or the emergency braking were quickly applied now*.

The advisory aiding presents an optimal speed profile—optimal in terms of total cost (energy consumption plus a weighted schedule deviation) under the constraints of schedule, speed limits, passenger ride quality, and train propulsion and braking capacities. If the human operator kept precisely to such a profile, he or she would have a better speed-control performance than by mentally performing the various calculations required for reaching the optimal control decisions.

Natural questions regarding the three proposed concepts of aiding are how to provide the proposed aiding and whether displaying all this aiding would provide too much information and overload the locomotive engineer. To answer these questions, the proposed individual aids were integrated into two displays, each containing different levels of aiding: the *predictor display* contained only the preview and the predictive aiding, and the *advisor display* contained the preview, the predictive and the advisory aiding. A conventional high-speed train cab environment was also implemented as a baseline for comparison purposes and is referred to as the *basic display*.

A preliminary human-in-the-loop experiment was conducted to investigate locomotive engineer performance with the preview display (the predictor display without the predictive aiding), because the preview is the basis of the predictor and the advisor displays. The results of the preliminary experiment strongly indicated that preview enhances safety by reducing speed violations and lowering workload. In spite of subjects' minimal experience, preview also showed promise for improving schedule adherence and station-stop accuracy (Appendix A).

Based on 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. The *independent variable* (variable manipulated by the experimenter) of the main experiment—aiding—had three levels: (1) no aiding—with the basic display, (2) preview and predictive aiding—with the predictor display, and (3) aiding level 2 plus the advisory aiding—with the advisor display. These displays will be described in detail in the next section.

The *dependent variables* (observed and measured variables) included (1) objective performance measures: situation awareness, speed compliance, station-stopping accuracy, energy consumption, schedule adherence, and passenger ride quality, and (2) subjective measures of workload (in four categories: time pressure, mental effort, stress, and overall workload).

To evaluate these dependent measures, three types of test runs were designed: (1) *routine speed control*, (2) *speed control under emergency scenario*, and (3) *speed control with secondary task*. Routine speed control was designed to measure performance under normal operation. This test run presented a hypothetical ideal situation where the locomotive engineer's task was speed control only, and where signals were always green throughout the trip. *Speed control under emergency scenario* was designed to investigate subjects' situation awareness via the timeliness and appropriateness of their decisions in handling unexpected situations (Hendy, 1995). The emergency scenario simulated a situation in which signals were suddenly changed to more restrictive levels due to either an obstruction or a defect of the track at some distance ahead. *Speed control with secondary task* was designed to indirectly evaluate visual workload associated with the displays. This test run allowed for the objective measurement of subjects' spare visual capacity via their performance on a simple, first-order, secondary tracking task. It is generally assumed that if the secondary task does not intrude on the primary task, the better the secondary task performance (i.e., the smaller the tracking error), the lower the visual attention demanded by the primary task (O'Donnell and Eggemeier, 1986). For all three types of test, incentive systems were devised to ensure that subjects did their best on speed control, made timely decisions in case of the emergency situation, and maintained speed control performance at the expense of the secondary task.

Several advantages of the advanced displays (predictor and advisor displays) were hypothesized. The advanced displays should (1) improve the locomotive engineer's situation awareness because the advance signals provide salient preview and, thus, attract the locomotive engineer's attention, and enable anticipation as well as timely response; (2) reduce the locomotive engineer’s visual workload—there should be little or no need for the locomotive engineer to intensely scan the fast moving field of view to search for signals since they are displayed inside the cab; (3) reduce the locomotive engineer's reliance on memory of track details—the previewed information on speed limits, track geometry, and so on, should help to reduce locomotive engineer’s mental workload of memory retrieval; (4) reduce the locomotive engineer’s mental effort of exercising his or her mental model of the train dynamics and, thus, improve the quality of decision-making on speed control—unnecessary use of emergency braking were expected to decrease with the use of the predicted speed profiles (the predictive aiding). Without the predictive aiding, the locomotive engineer would have to estimate the braking distance in order to make a proper judgment as to the use of emergency braking.

The advisor display was also expected to reduce energy consumption. The predicted full-service and emergency braking curves would serve as a guideline or basis for strategic application of control forces in following the optimal speed profile. However, since the advisor display has the maximum amount of aiding information, we were concerned that subjects might experience information overload that would degrade performance. The test of speed control with secondary task, mentioned earlier, was designed to address this concern.

2. METHOD

2.1 HIGH-SPEED RAIL SIMULATOR

As part of the research, a real-time distributed high-speed rail simulator was developed for the Volpe National Transportation Systems Center (VNTSC) to study human factors issues associated with the operation of high-speed trains (Appendix B). The human-in-the-loop experiments of this research were conducted on this simulator with three Silicon Graphics workstations (one Indigo2 Extreme and two Personal Irises 4Ds). One workstation was used to display the cab indicators and instruments, to compute dynamic propulsion and brake forces of the train (a realistic model of longitudinal dynamics was used) (Appendix C), to conduct computations associated with the decision aids, and to provide a control interface (throttle, computer mouse and keyboards). Another workstation simulated the out-the-window view and was physically placed side by side with the cab displays. The third workstation was used as a Central Traffic Control workstation. All three workstations exchanged data through a local-area-network link.

2.2 THE DISPLAYS

Figures 2-1 to 2-3 show the basic, the predictor and the advisor displays, respectively, in a common simulated cab environment. The cab environment contained an automatic train protection (ATP) system, an emergency brake, an alert system, and a throttle-position indicator. (Other indicators such as door open/close indicator, call-up schedule display, text message input and output displays, braking pipe pressure, electric power level, and so on, will not be discussed since their functions were not used in this experiment.) These functional components and indicators, common to all three displays, are described below.

The throttle-position indicator corresponding to the dual-use throttle was a horizontal grid bar located under the frame of the central region in Figure 2-1 (item 8). The center grid of this indicator corresponded to the center notch position of the throttle. Functionally, this position of the throttle was neutral; no braking or traction was applied. To the left of the center grid, braking was displayed; to the right, traction level. The throttle was capable of continuous-force application (as compared to notched levels) and its position was displayed accordingly. The grid lines on the force indicator were provided as measures of force level at every 10% of the current maximum braking or traction.

Functions related to speed control were provided on the right side of the screen. Two functions are shown in Figure 2-1: the automatic train protection (ATP) system and the emergency stop

(ESTOP). The emergency stop could be activated manually via a key stroke (F12 key) or a mouse-click on the ESTOP indicator. The ATP system warned the locomotive engineer (by blinking its triangular indicator) when the speed of the train was above the speed limit. It automatically activated the emergency stop when (1) the train was more than 15 km/h above the speed limit, or (2) the speed of the train was within the 15 km/h overspeed tolerance for more than 20 seconds. Emergency braking, whether activated manually or automatically, could not be reset until the train had fully stopped.

The status display of the alert system (ALERT), located just under the door indicator, generated a blinking-yellow warning with a random period in the range from 40 to 80 seconds. Once the warning was active, the alert system expected an acknowledgement or response from the operator. The response could be either a key stroke (Esc key) or a throttle maneuver. (An alert system is "intelligent" if it takes throttle maneuvers as responses.) If no response was received in 10 seconds after the initiation of the warning, the alert status display changed to blinking red accompanied by beeps. If no response was received in another 10 seconds, emergency braking was automatically activated. Again, emergency braking could not be reset until the train had come to a complete stop.

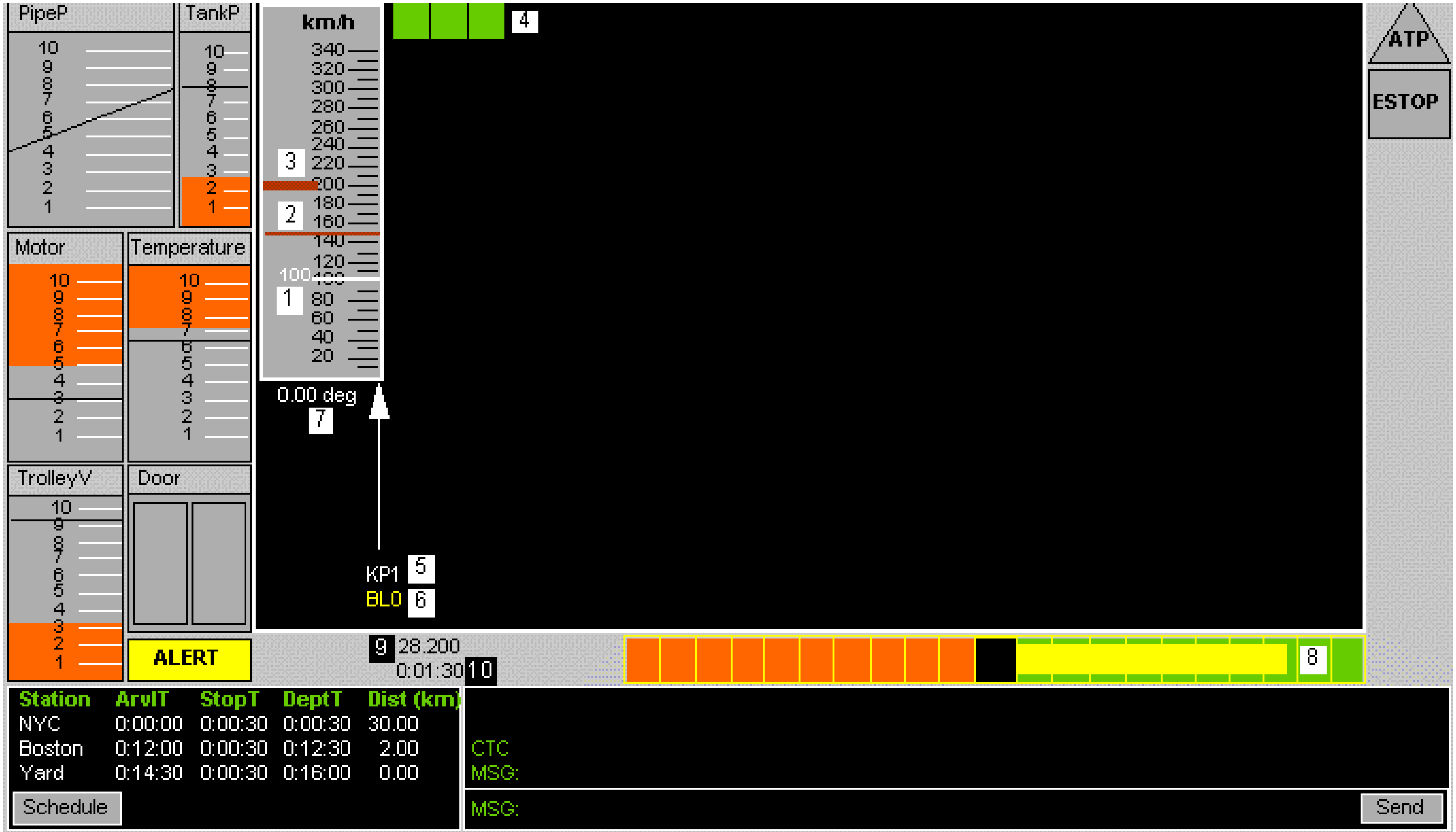


Figure 2-1. Control Panel and the *Basic* Display. 1: Current speed 2: Civil speed limit of current block 3: Civil speed limit of next block 4: Signal of current block 5: Current kilmeter post 6: Current block number 7: Grade of track at current location 8: Force indicator (traction or braking) 9: Distnace to next station 10: Current time.

2.2.1 The Basic Display

The speedometer, located in the center of the screen, indicated current speed (item 1 in Figure 2-1), speed limit of the current block (item 2), and speed limit of the next block (item 3). To the upper right of the speedometer was the three-lights cab signal (item 4) whose aspect (color combination) depended on the track condition ahead (e.g., being occupied by a train). With the 6-block 7-aspect signal system used in this study (Table 2-1), and with the notation of G—*green*, Y—*yellow*, and R—*red*, the seven signal aspects were 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). Preliminary background on the functionality of such a signal system is provided in Appendix D.

Table 2-1. Signal Aspects and Signal Speeds

*Signal Aspect**	*Signal Speed (km/h)*	*Definition of the Aspect*
GGG	300	Proceed
GYG	300	Proceed approaching next signal at 270 km/h
YGY	270	Proceed approaching next signal at 220 km/h
YYY	220	Proceed approaching next signal at 160 km/h
YRY	160	Proceed approaching next signal at 80 km/h
RYR	80	Proceed preparing to stop
RRR	0	Stop, do not enter.

* *G—Green, Y—Yellow, R—Red.*

Geometrical information about the current location of the train was provided below the speedometer. The grade (in degrees) of the track at the current location was shown under the speedometer (item 7). The number of the block where the train was currently located (item 6) and the number of the kilometer-post that the train had just passed (item 7) were shown below the lower right corner of the speedometer with the symbols BL followed by the block number and KP followed by the kilometer post number. In addition, the distance to the next station was displayed to the lower right of the block number (item 9), with the current time below (item 10).

2.2.2 The Predictor Display

The predictor display (Figure 2-2) presented the following advance information with an operator-adjustable preview range from 0.1 to 20 km (via keyboard F5-F8 keys): kilometer posts (item 10), block boundaries (item 9), civil speed limits (items 2 and 3), signals (items 4 and 5), track elevation profile (item 6), and stations (item 16). The respective indicators in the predictor display are described below.

Preview of kilometer posts (item 10)—These were vertical (white) lines across the preview range. Counted from the origin of a trip, the kilometer post numbers were marked at the lower ends of the posts in the display. The preview of kilometer posts provided a distance scale for the rest of the previewed information. The current location of the train was marked by a white-arrowed line aligned with the right of the speedometer (item 8).

Preview of block boundaries (item 9)—These were thick, short (yellow) vertical lines with the corresponding block numbers marked at their top right. Block lengths vary along a line in practice. As a means of expediting the subjects' understanding the track environment, 2-kilometer blocks were adopted throughout the experimental track and, therefore, all block boundaries were aligned with the even-numbered kilometer posts.

Preview of elevation (item 6)—This was a side view of the track profile for the preview range, with the current location of the train as the horizontal reference. The elevation profile in Figure 2-2 is a horizontal straight line because the experimental track was flat.

Preview of stations (item 16)—A station within the preview range was indicated with a house-like (yellow) icon with the station name marked beneath it (here Boston, at the extreme right of the display).

Preview of civil speed limits (item 3)—For each block in the preview range, the civil speed limit was indicated by a horizontal (red) line. The level of the line corresponded to the civil speed limit of the block, with the speed level scale being provided by the speedometer.

Preview of signals (item 5)—For each block in the preview range, the signal was indicated by a set of three rectangular lights. For each block, the level of the base of the three signal lights corresponded to the *effective* speed level, which was the lower of the civil speed limit and the signal speed of the block. For example, if the signal was GGG, the bottom of the signal was aligned at the current speed limit level; if the signal was RYR and the civil speed limit of the block was 250 km/h, the bottom of the signal was aligned at the 80 km/h level. (Note that the speedometer provided the speed scale.) Therefore, unlike the cab signal in the basic display whose location remained unchanged when the signal aspect changed, the previewed signals relocated vertically depending on their signal levels.

The three predicted speed curves (items 11, 12, and 13) were 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).

2.2.3 The Advisor Display

The advisor display (Figure 2-3) incorporated the predictor display plus the optimal speed profile (that met all the given speed limits and got the train to the next station on time while minimizing energy consumption). Dynamic programming techniques were used to solve this highly constrained optimization problem (Appendix E).

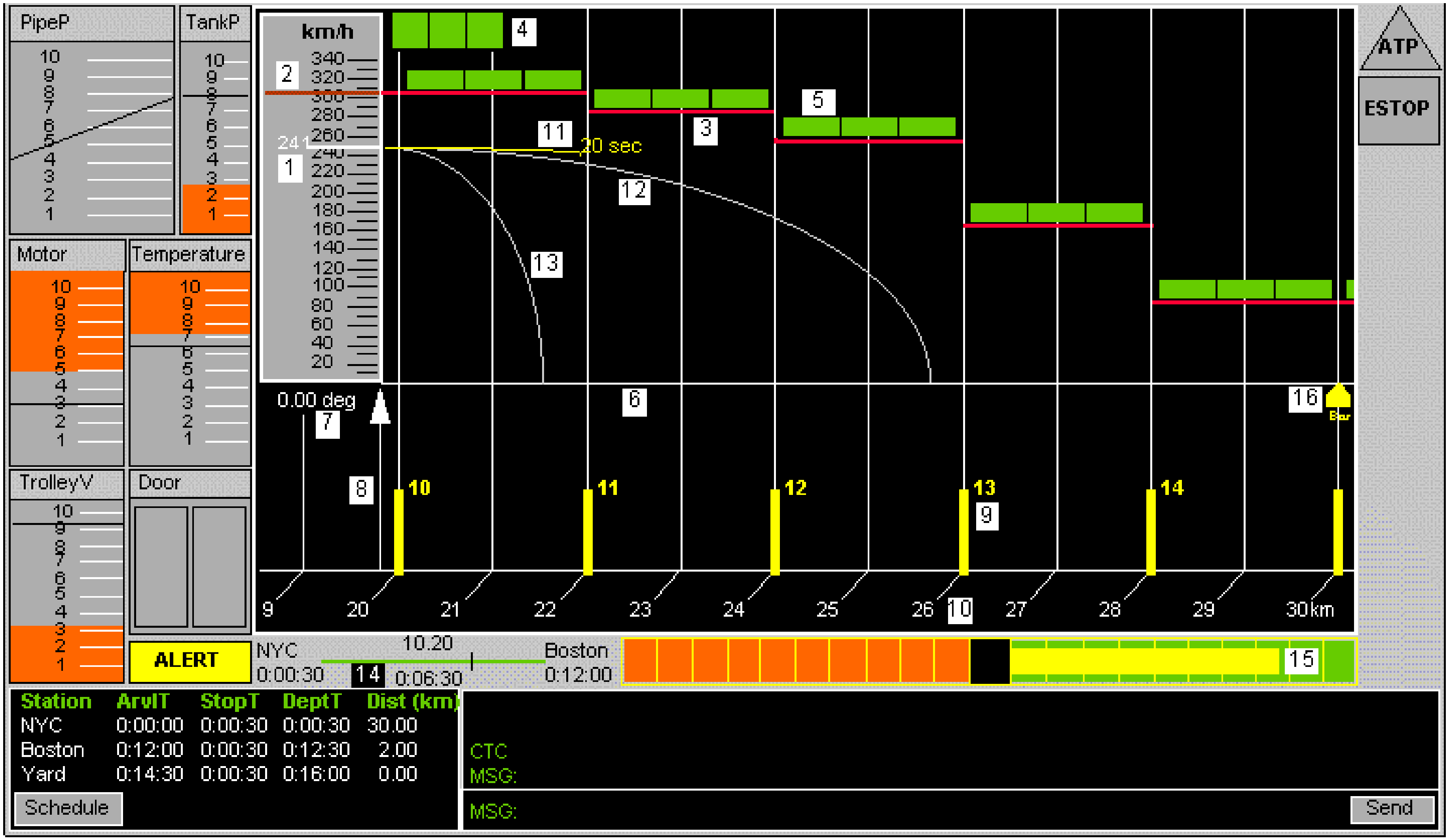


Figure 2-2. Control Panel and the *Predictor* Display. 1: Current speed 2: Civil speed limit of current block 3: Previewed civil speed limits 4: Signal of current block 5: Previewed signals 6: Previewed track elevation profile 7: Grade of current location 8: Location of train 9: Block boundary and number 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.

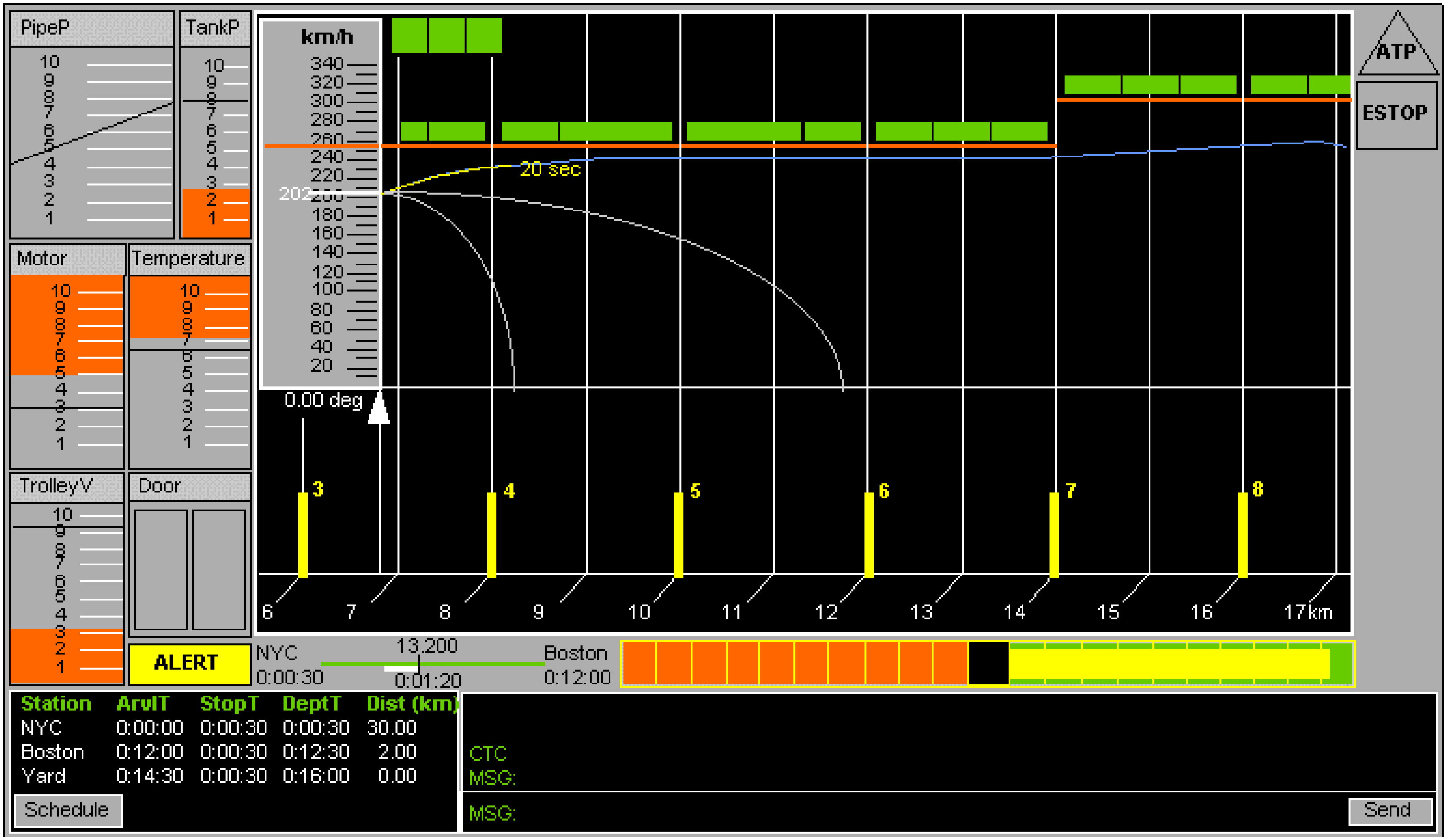


Figure 2-3. Control Panel and the *Advisor* Display. The curve across the preview range and under the speed limit profile is the advisor.

2.3 CONTROLS

The control interface between the subject and the train simulator for the main experiment consisted of two mechanisms: a dual-use throttle and keyboard keys. The throttle was programmed to be capable of both braking and propulsion, with each function allocated one half of the throttle throw. The throttle had a center notch to provide tactile feedback on its functional position (braking vs. propulsion). Keyboard keys were used for alert reset and for preview adjustment (F5-F8 keys).

2.4 TASKS

Three types of test runs were designed to measure different aspects of system performance: routine speed control, speed control under emergency scenario, and speed control with secondary task. These test runs encompassed three distinct tasks: *speed control*, *emergency handling*, and *secondary task*. Speed control was the only task present in test runs of routine speed control, the only task before the onset of the emergency situation in runs of speed control with emergency scenario, and the primary task in runs of speed control with secondary task.

The same short and simple test course (30 km, straight and flat), shown in Figure 2-4, and schedule (to be completed in 11.5 minutes) were used for all experimental runs. The out-the-window view was an abstract night view which eliminated distractions and thus enhanced the recognition of landmarks.

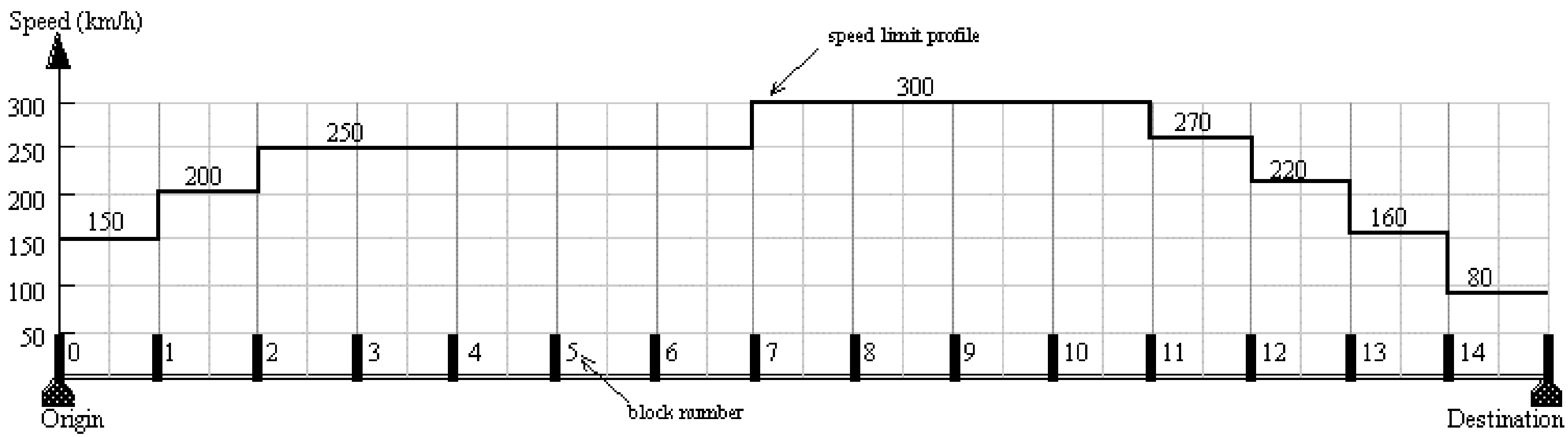


Figure 2-4. Test Course.

2.4.1 Speed Control

In each run, the train was initially positioned at the departing station, and was to be started according to a predefined schedule. Subjects were instructed that given control manipulations (a certain amount of braking or accelerating) were to be executed at specific points along the test course in order to produce the minimum-cost trip (even when the optimal speed profile was not shown as in the runs with the basic and the predictor displays). Corresponding to what professional locomotive engineers learn to do, important landmarks and "points of no return" in the out-the-window view were used by subjects to recognize locations where certain throttle manipulations were due. There were two types of landmarks along the track: some located immediately before each block boundary, and others located before critical points for optimal throttle manipulation (Figure 2-5). The former landmarks alerted subjects to an upcoming new block, the latter got subjects psychologically ready for a major control manipulation.

When the train was within the station range (800 meters before the station) at a speed of about 70 km/h, a head-up display (Figure 2-6), designed to provide cues for station stopping, was projected onto the "windshield," i.e., the computer screen of the out-the-window view. When operating with the basic display, a technique of using the landmarks together with the head-up-display for station-stopping was necessarily used (Appendix F). The train was stopped at the station point when the head-up display overlapped with the perspective view of the back wall of the station building. When operating with the predictor or the advisor display, the predicted speed curves were used to guide station stopping, although the landmarks and the head-up-display were still available.

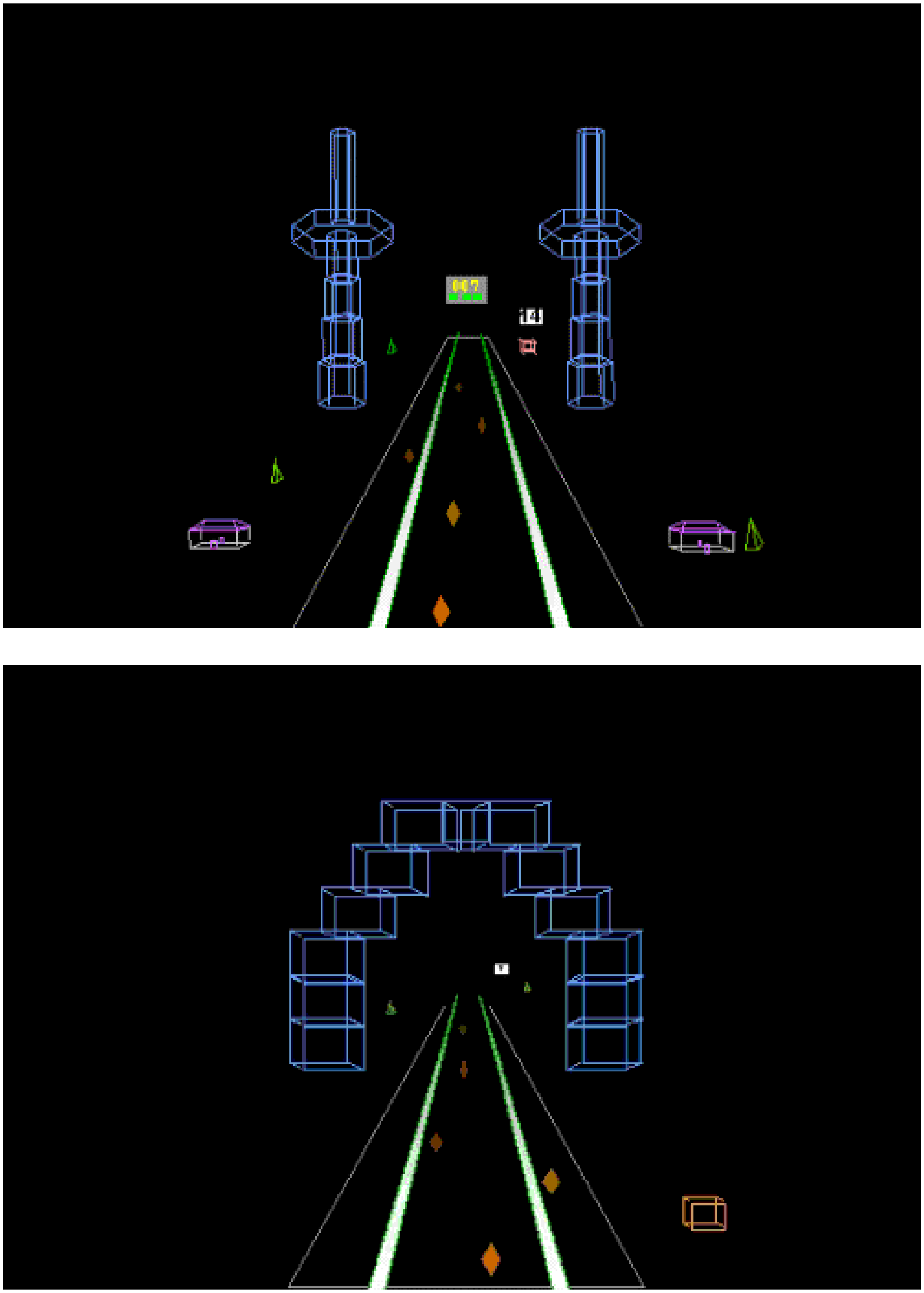


Figure 2-5. Landmarks in the Out-The-Window View. *Top*: Landmark (two blue towers) before a block boundary (block 7) or kilometer post 14. *Bottom*: Landmark (red overhead bridge) before a point of major throttle manipulation (start coasting).

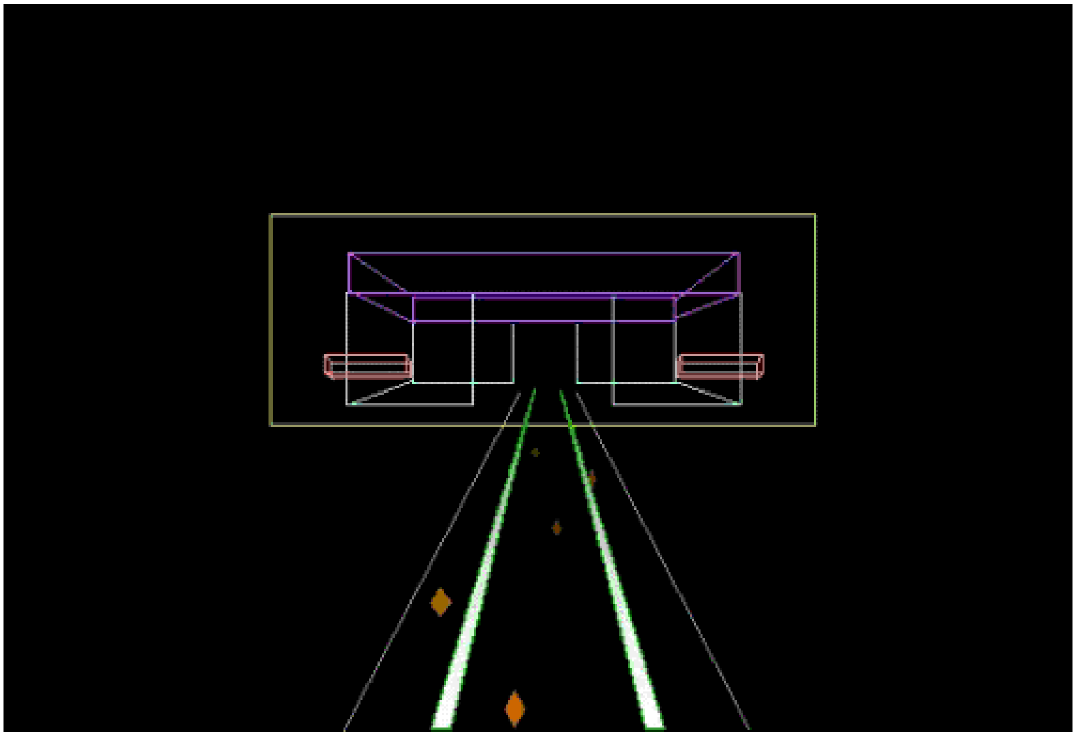
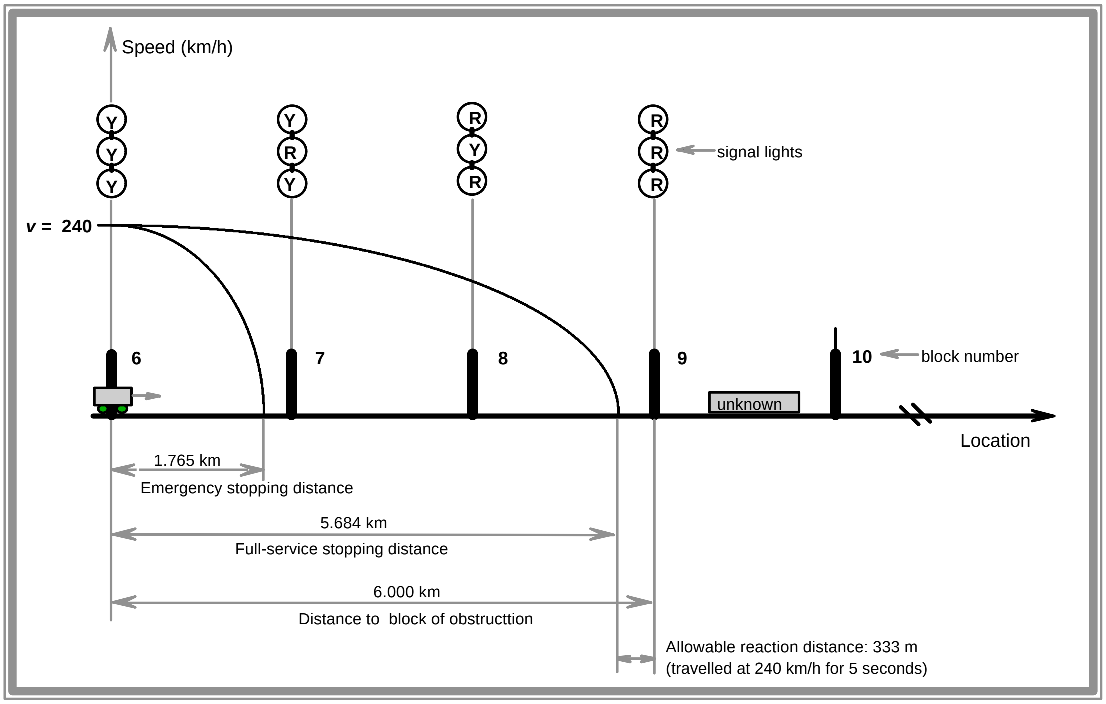


Figure 2-6. Head-Up Display for Approaching Station. The largest rectangle in this "snapshot" is a head-up display (HUD) (yellow) that was projected on to the screen when the train was 800 meters away from the station point. The *station* is a wire-frame building (purple and blue) with an entrance "door" 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 the perspective view of the whole back wall of the station becomes the same size as the HUD, the train is at the station point.

2.4.2 Emergency Handling

The emergency scenario, assuming the ATP (automatic train protection) system had failed, was designed to occur while the train was cruising at 240 km/h (Figure 2-7). At the onset of the signal event, subjects 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. After application of full-service braking, the 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.



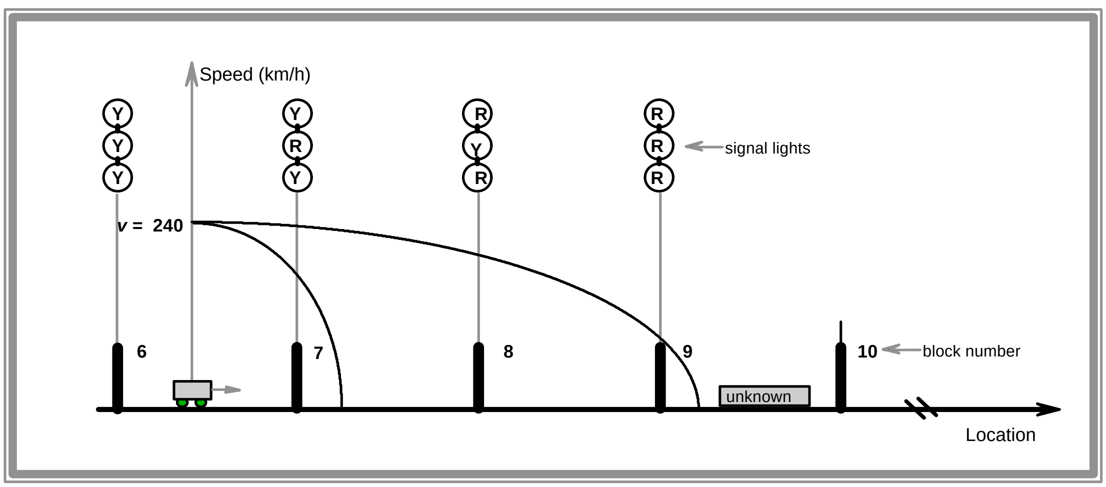


Figure 2-7. Signal Event (at Block 6). *Top*: At the onset of the event. *Bottom*: After a delay in reaction of more than 5 seconds. The signal light notation is R—*red*, Y—*yellow*. A signal of YYY (220 km/h signal speed) implies that the next block should be more restrictive, the one further ahead 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 locomotive engineer 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).

2.4.3 Secondary Task

The secondary task (Figure 2-8) was a simple first-order tracking task, presented to the subject in the upper left corner of the display (in place of the pipe and tank pressure displays). The state of the secondary system increased or decreased (visually moving up or down in the secondary task window) at a constant rate (0.12 cm/sec). The reference input of the system changed discretely at a random cycle with an average period of one minute. 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.

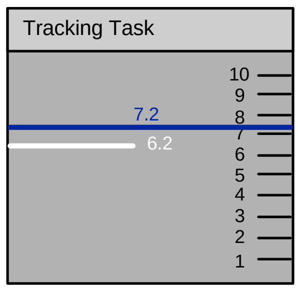


Figure 2-8. The Secondary Tracking Task.

2.5 SUBJECTS

Twelve subjects (one female, eleven male, with ages ranging from about 20 to 25) completed the experiment. The data of a thirteenth subject was discarded because of his apparent violation of a basic rule (i.e., except for avoiding a potential red-light overrun, no emergency braking should be initiated by the subjects, especially when approaching a station) that led to incomplete performance data. Six subjects failed to pass the evaluation during training and did not proceed to the experimental tests.

All subjects (students from the Massachusetts Institute of Technology) were pre-selected with the following two criteria: (1) at least 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 participated in the preliminary experiment.

Subjects were paid for their performance during both training and testing. The three top performers won cash prizes. The pay for each test run consisted of a base rate plus a performance-based bonus. In particular, for runs of routine speed control, the bonus was awarded depending on performance in five measures as shown in Table 2-2.

Table 2-2. Bonus Comparison Table For Speed Control

Performance	Bonus 5	4	3	2	1	0
Station Overshoot Station Undershoot [meters]	0 ~ 2 0 ~ 2	2 ~ 3 2 ~ 4	3 ~ 4 4 ~ 6	4 ~ 5 6 ~ 8	5 ~ 6 8 ~ 10	≥ 6 ≥ 10
Arrival Late Arrival Early [seconds]	0 ~ 8 0 ~ 10	8 ~ 12 10 ~ 14	12 ~ 16 14 ~ 18	16 ~ 20 18 ~ 22	20 ~ 24 22 ~ 26	24 ~ 60* ≥ 26
Distance Oversped [meters]	0	0 ~ 70	50 ~ 144	144 ~ 210	210 ~ 280	≥ 280
Large Jerks [times]	0	1	2	3	4	≥ 5
Total Cost [% optimal Cost]	0 ~ 20	20 ~ 30	30 ~ 40	40 ~ 50	50 ~ 60	≥ 60

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

For runs of speed control under the emergency scenario, 25 bonus points were awarded if a red-light overrun was avoided with full-service braking alone. Otherwise, the following rules applied:

- When emergency braking was activated to avoid a red-light overrun, between 10 and 20 points were awarded depending on the activation-speed. The lower the activation-speed, the more points were awarded. Under the assumption that subjects would rationally initiate full-service braking as soon as they detected the signal change, the emergency braking activation-speed could then be indirectly gauged by the distance between the train's stop point and the red lights. The shorter the distance the train was stopped before the red lights, the lower the activation-speed had been.

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

The incentive for the runs of speed control with the secondary task combined performance in both speed control (Table 2-2) and tracking. To ensure that the tracking task was treated as secondary, the incentive for the tracking task was based on the speed control performance, ranging from increasing the speed control bonus by 10 percent to losing all of it.

2.6 PROCEDURES

2.6.1 Training

The training consisted of three sessions and required a total of five and a half hours per subject to complete. The first session (two and a half hours per subject) focused on teaching basic concepts associated with operating a high-speed train and the simulator (Appendix G). A written test (90% to pass) was conducted to examine each subject's grasp of the contents taught during the session (Appendix H).

The second session (two and a half to three hours per subject, at least 6 hours after the first session) focused on the skills of operating the train on the test course with each display. Each subject practiced a total of nine runs over the test course—three consecutive *routine speed controls* with each of the three displays. The sequence of the three consecutive runs was permutated between subjects to attenuate learning effects that might affect the evaluation of learning curves. Subjects were provided with track and civil speed profiles (posted on the wall), a guide for optimal throttle manipulation (Appendix F), a copy of the profile of stopping-distance as a function of initial speed (Appendices I and J), and a copy of the bonus system (Appendix K). Immediate feedback was provided via both the experimenter'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. Subjects were qualified by a written test (90% to pass) as well as "road" evaluations conducted during the practice runs (Appendix L).

The last session of training (half an hour per subject) took place the day after the hands-on training and immediately before the experimental tests. Subjects 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 were different from those in the experimental tests). This session also trained subjects to perform the secondary task while operating the train. Emphasis was given on the subjects' understanding of the task's relatively lower priority to the primary speed control task.

2.6.2 Testing

In the testing session (two and a half hours per subject), with the three displays and three run types, each subject performed nine test runs in a randomly assigned sequence. The sequences were carefully arranged through a within-subject design to reduce anticipation of the emergency event and counterbalance learning effects. (No *Jerkometer* was present during the testing, with the assumption that subjects, through training, had acquired the skill of providing good ride quality.) To avoid any anticipation that might affect performance, subjects were not told the total number of test runs. A questionnaire for subjective assessment of workload (Appendix M) was administered immediately after each run. Subjects' relative rating of overall workload associated with the displays as well as their retrospective comments and rankings of the displays were obtained via a post-experiment questionnaire (Appendix N).

3. RESULTS

The results are organized into five sections. The first three analyze performance measures obtained from the three types of test runs: *routine speed control*, *speed control under emergency scenario*, and *speed control with secondary task*. In the fourth section, subjective ratings on overall workload and rankings of the displays are compared. Finally, subjects' performance during the hands-on training is presented

3.1 ROUTINE SPEED CONTROL

3.1.1 Total Cost

The total cost of a trip is the sum of the 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.

A nonparametric Friedman two-way ANOVA performed on total cost (Figure 3-1) shows a significant effect of the displays (F_r = 10.17 k = 3, N = 12, p < 0.01) (Siegel and Castellan, 1988). Post hoc comparisons reveal a significant difference in total cost between the advisor

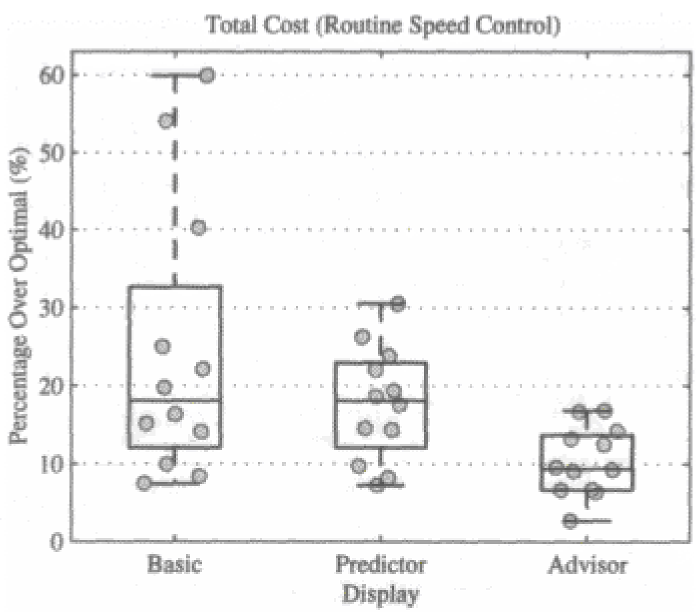


Figure 3-1. Total Cost.

display ($\overline{X}$ = 10.3% over the minimum total cost) and the basic display ($\overline{X}$ = 24.4% over the minimum total cost) (p <0.05). In effect, the advisor display reduced the total cost by 11% with respect to the basic display. In addition, the three box plots (see p. xi for definition) of Figure 3-1 show a 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). The predictor display, although reducing the total cost by 5% with respect to the basic display, was not significantly different in total cost from either the basic or the advisor display.

3.1.2 Station-Stop Deviation

Station-stop deviation is the absolute difference between the actual stopping point and the station. Both advanced displays reduced the mean station-stop deviation from 12.7 m with the basic display to under 1 m (Figure 3-2). One outlier with the predictor display was excluded from the calculation because it resulted from the subject's anticipation of the last test run. Due to the unequal variances, a nonparametric Cochran Q test was performed after converting the data into to two categories: 1—if the deviation is less than 2 meters, or 0—otherwise (Siegel and Castellan, 1988). This test disclosed that the effect of aiding on station-stop deviation was indeed highly significant (Q = 18.18, df = 2, N = 12, p < 0.001).

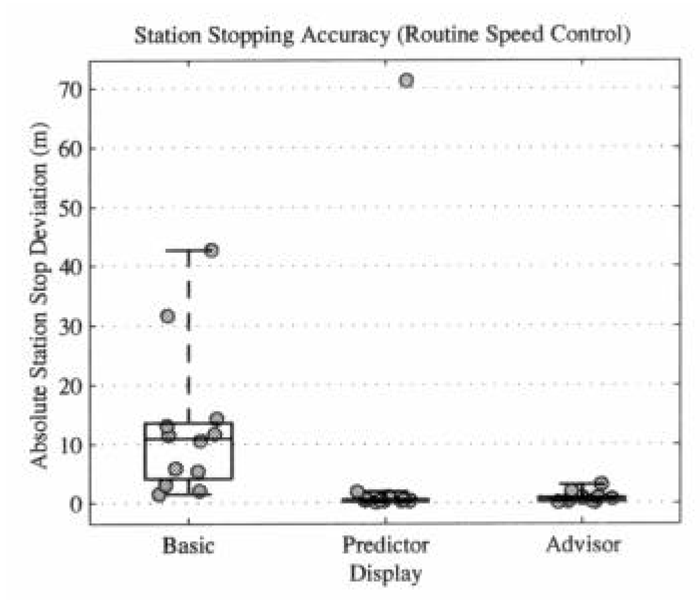


Figure 3-2. Station-Stop Deviation.

3.1.3 Schedule Deviation

Schedule deviation is the absolute difference between the scheduled arrival time and the actual arrival time. No significant effect of the displays on schedule deviation (Figure 3-3) was found through a nonparametric Friedman two-way ANOVA by ranks. Since nonparametric statistical tests usually do not use the full information of the original data, the analysis results tend to be conservative with regard to making Type I errors (Siegel and Castellan, 1988). Therefore, a repeated measures ANOVA was performed on the schedule deviations. Results show that the displays had a significant effect on schedule adherence ($F_{(2, 22)} = 4.143$, $p < 0.05$). Scheffé's tests found that there was a significant difference in schedule deviation between the advisor display ($\overline{x}$ = 3.8 sec) and the basic display ($\overline{x}$ = 11.1 sec) ($p < 0.05$). There was a trend of reduced mean schedule deviation with the predictor display ($\overline{x}$ = 5.4 sec) compared to that with the basic display ($\overline{x}$ = 11.1 sec) ($p = 0.1$). No statistical difference in schedule deviation was found between the predictor and the advisor displays. Note that the apparent differences in variances among the data sets do no invalidate the results because the ANOVA is not sensitive to violations of the assumption of homogeneity of variances when cell sizes are equal, as they are in this case (Shavelson, 1988).

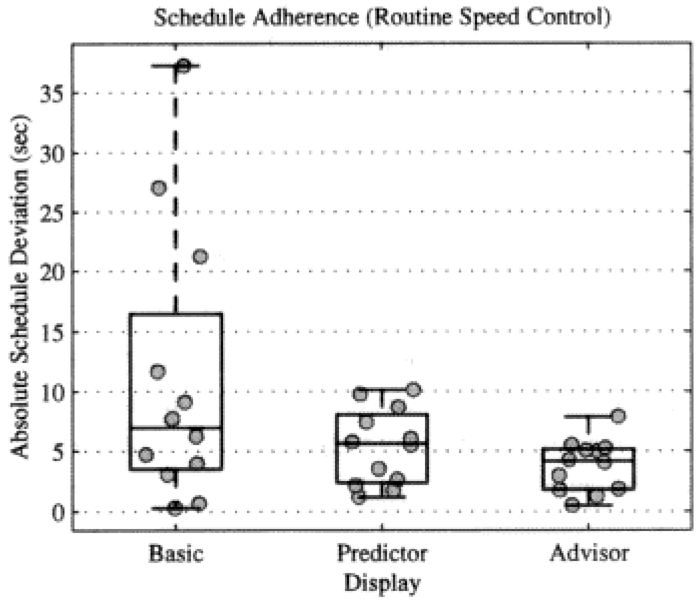


Figure 3-3. Schedule Deviation.

3.1.4 Over-Speed Distance

The distance traveled when the train was above the current speed limit during a test run was collected as a measure of speed compliance. No subject committed a speed violation in any run with any display.

3.1.5 Ride Quality

Ride quality was measured in terms of the number of jerks incurred by the subject's abrupt throttle manipulation in a test run. 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 0.06 g/s. There was no jerk with the basic, one with the predictor, and a total of two jerks with the advisor display. The increase in number of jerks with increased aiding was not found to be significant by a nonparametric Cochran Q test ($Q = 2$, $df = 2$, $N = 12$, $p = 0.42$).

3.1.6 Workload: Immediate and Absolute Ratings

Workload was measured with a subjective rating of time pressure, mental effort, and stress immediately after each test run on a discrete scale from 1, the lowest, to 7 the highest (Appendix M). Table 3-1 presents the mean ratings for the displays.

A repeated measures ANOVA was performed on each of the three measures of workload. First, as expected, time pressure was not affected by the displays ($F_{(2, 22)} = 0.94$, $p = 0.37$). This confirms the experimenter's observation that subjects did not show any indications of busyness nor were they involved in overlapping activities in runs with routine speed control. Second, ratings of mental effort varied significantly across the displays ($F_{(2, 22)} = 9.72$, $p < 0.001$). In particular, subjects rated mental effort with the predictor display ($\overline{X} = 3.17$ on a scale of 1 to 7) and the advisor display ($\overline{X} = 2.96$) significantly lower than that with the basic display ($\overline{X} = 4.42$) (Scheffé's tests, $p < 0.005$). Third, aiding had a highly significant effect on subjective ratings of stress ($F_{(2, 22)} = 7.13$, $p < 0.005$). A significant difference in ratings of stress was found between the advisor display ($\overline{X} = 2.67$ on a scale of 1 to 7) and the basic displays ($\overline{X} = 3.83$) (Scheffé's test, $p = 0.005$). Stress with the predictor display ($\overline{X} = 3.08$) was rated lower than that with the basic display, although not statistically significant at the 5% level (Scheffé's test, $p < 0.1$). Finally, it can be observed from Table 3-1 that the higher the aiding level, the lower the mean rating on all three workload measures. It should also be noted that the maximum mean rating on workload was only 4.4 on the rating scale from 1 (lowest) to 7 (highest workload).

Table 3-1. Mean Subjective Ratings on Workload (Routine Speed Control)

	Subjective Ratings on		
Display	*Time Pressure*	*Mental Effort*	*Stress*
Basic	3	4.4	3.8
Predictor	2.5	3.2	3.1
Advisor	2.4	3.0	2.7

3.2 SPEED CONTROL UNDER THE EMERGENCY SCENARIO

3.2.1 Reaction Times

The reaction times to the emergency signal event are presented in Figure 3-4. Since the signal change occurred while the train was cruising at 240 km/h which required 34% of full traction to maintain, subjects had to bring the throttle from 34% full traction, through the neutral, to 100% of braking. The reaction time is thus defined as the span from the time of signal onset to the time when the throttle was brought to the neutral position. A nonparametric Friedman two-way ANOVA by ranks on the reaction times, reveals that the effect of displays on subjects' reaction times was highly significant (F_r = 10.17, k = 3, N = 12, $p < 0.01$). Post hoc comparisons found that the mean reaction time with either the predictor or the advisor display (both $\overline{X}$ = 1.4 seconds) was significantly shorter than that with the basic display ($\overline{X}$ = 8.6 seconds). In addition, the three box plots (see p. xi for definition) in Figure 3-4 show a much wider dispersion of the reaction times with the basic display than those with the predictor and advisor displays. In fact, 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.

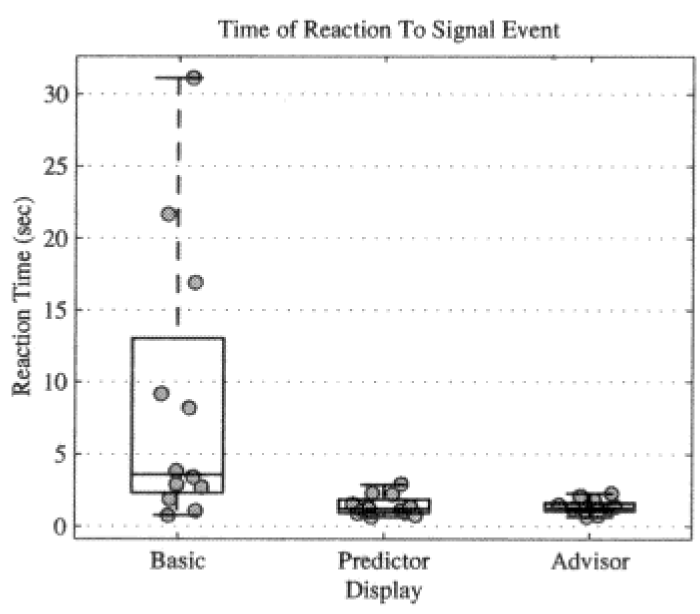


Figure 3-4. Reaction Times.

3.2.2 Emergency Handling

Results of emergency handling are summarized in Table 3-2. No red-light overrun was committed with the advanced displays, as compared to two such incidents (16.7%) with the basic display. Also, with the advanced displays, subjects responded to 96% (23 out of 24) of occurrences of the event fast enough to safely stop the train before the occupied block without having to resort to emergency braking, compared to only 33% (4 out of 12) with the basic display (Cochran Q test, $Q = 14.25$, $df = 2$, $N = 12$, $p < 0.001$). In other words, 67% (8 out of 12) of all subjects with the basic display had to use the emergency brake. Further, the speed at which the emergency braking was activated with the predictor display ($\bar{x}$ = 19 km/h, one datum only) was much lower than that with the basic display ($\bar{x}$ = 108 km/h, range of 40 to 183 km/h).

Table 3-2. Reaction Times and Response Types to Emergency Scenarios

	Outcome of Eventful Runs				
		Red-Light Overrun with*		*Safe Stop* with*	
Display	*Mean Reaction Time (seconds)*	*Emergency Braking*	*Full-Service Braking*	*Emergency Braking*	*Full-Service Braking*
Basic	8.6	2/12	0	6/12	4/12
Predictor	1.4	0	0	1/12	11/12
Advisor	1.4	0	0	0	12/12

* Expressed in ratios of stated events to total events.

3.2.3 Workload: Immediate and Absolute Ratings

Table 3-3 shows the mean subjective ratings of time pressure, mental effort, and stress for runs under the emergency scenario. All three measures of workload were significantly affected by displays as found by a repeated measures ANOVA ($p < 0.05$). Post hoc comparisons (Scheffé's tests) show that both the advisor and the predictor displays had significantly lower ratings on mental effort than the basic display. The advisor display also had significantly lower ratings on stress than the basic display. No effects of the displays on time pressure were found through post hoc comparisons, although the repeated measures ANOVA was significant.

Table 3-3. Mean Subjective Ratings on Workload (Under Emergency Scenario)

	Subjective Ratings on		
Display	*Time Pressure*	*Mental Effort*	*Stress*
Basic	3.8	4.8	4.7
Predictor	2.6	3.8	3.8
Advisor	2.9	3.8	3.7

3.3 SPEED CONTROL WITH SECONDARY TASK

3.3.1 Spare Visual Capacity

Performance on the secondary task, reflecting spare visual capacity, was measured by the root-mean-squared (RMS) tracking error over every half-kilometer of the test course (with an error sampling rate of 5 Hz). The results on spare visual capacity (Table 3-4) were obtained from the individual RMS tracking errors of the subjects as shown, for example, in Figure 3-5. First, 75% of the subjects (9 out of the 12) committed their largest tracking error 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 by a Friedman two-way ANOVA by ranks, the trend was strong ($p = 0.063$). Second, as expected, subjects' average tracking error was significantly higher over the last kilometer before the station than their tracking error averaged over the first 29 kilometers (paired *t*-test, $p < 0.05$).

Table 3-4. Performance on Secondary Task

	Performance Measure		
Display	*Num. of Highest Tracking Error*	*Mean Tracking Error—En route* (x0.4 cm)	*Mean Tracking Error— Appr. Station* (x0.4 cm)
Basic	3	2.0	0.8
Predictor	5	1.9	0.9
Advisor	4	1.8	0.9

3.3.2 Ride Quality

For ride quality, similar observations were made with the secondary task as with routine speed control—two jerks with the basic, four with the predictor, and three with the advisor display. No significant effects of the displays on ride quality were found.

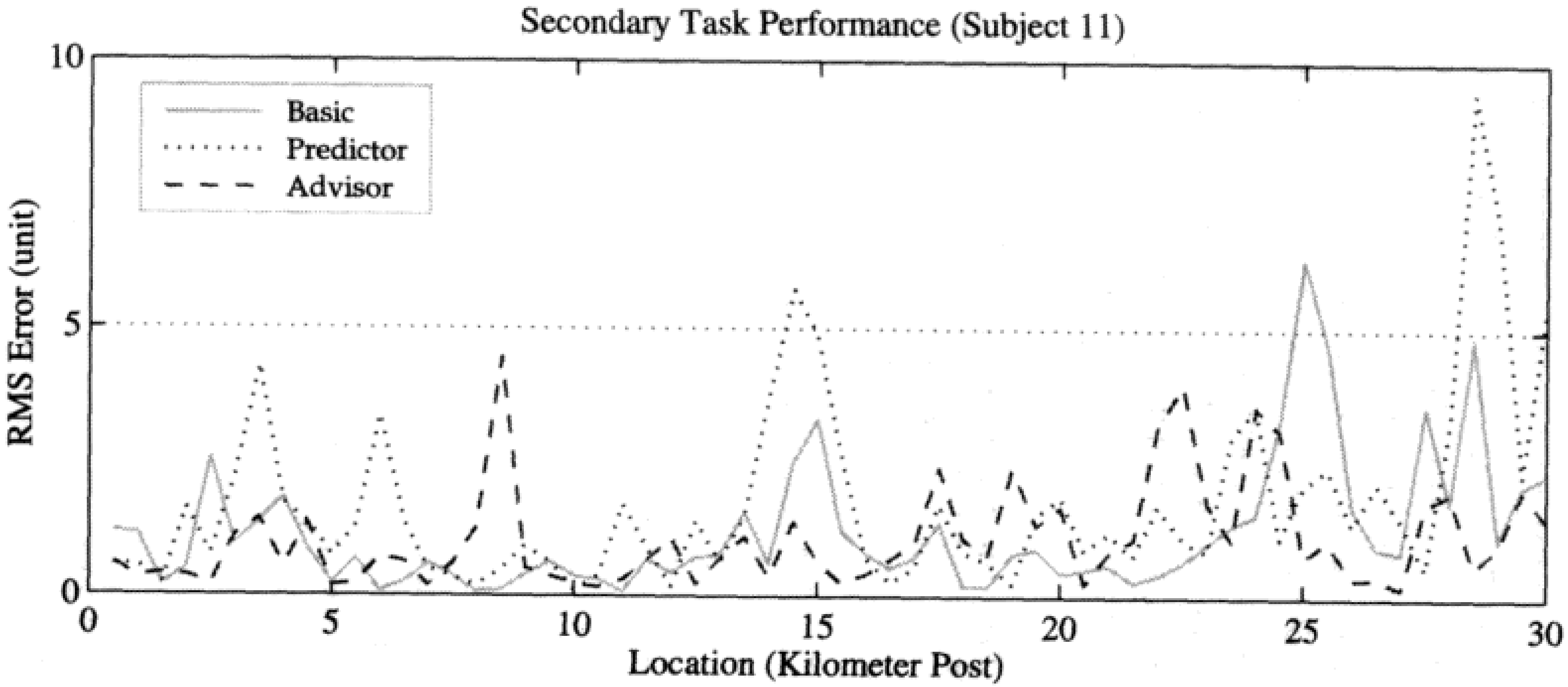


Figure 3-5. Tracking Errors of the Secondary Task by Subject 11.

3.3.3 Workload: Immediate and Absolute Ratings

Table 3-5 shows the mean workload ratings for runs with the secondary task. There was significant effects of the displays on stress, but not on time pressure and mental effort (a repeated measures ANOVA). Post hoc comparisons reveal that only the predictor display had significantly lower ratings of stress than the basic display (Scheffé's test, $p < 0.05$).

Table 3-5. Mean Subjective Ratings on Workload (With Secondary Task)

	Subjective Ratings on		
Display	*Time Pressure*	*Mental Effort*	*Stress*
Basic	4.8	4.7	4.8
Predictor	3.4	4.3	3.8
Advisor	3.8	4.3	4.1

3.3.4 Verification of Non-Intrusiveness

To ascertain that the secondary task did not affect performance on the primary task, paired *t*-tests were conducted to compare the dependent variables between runs with routine speed control and runs with the secondary task for each display. No significant differences were found for any of the measures with any display. This shows that differences in secondary task performance truly reflect differences in spare visual capacity.

3.4 OVERALL WORKLOAD AND DISPLAY PREFERENCES

Subjective workload was also assessed through the post-experiment questionnaire. The 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 (Appendix N). (A rating larger than 100 meant higher workload than that for all test runs with the basic display. Correspondingly, a rating smaller than 100 meant lower workload than that for all test runs with the basic display.)

The overall workload ratings for each display are plotted in Figure 3-6. Most subjects (83%, 10 out of 12) indicated that the basic display imposed the highest overall workload ($\overline{X} = 100$), followed by the predictor display ($\overline{X} = 70$) and the advisor display ($\overline{X} = 56$). One subject thought that while the basic display imposed a higher workload than the two advanced displays, the advisor display imposed a higher workload than did the predictor display—contrary to the majority. He and another subject, who rated the advisor display as imposing the highest workload among the three displays, commented that following the advisor required additional attention or more attention than driving with the other displays.

These effects of the displays on ratings of overall workload, were found to be highly significant by a Friedman two-way ANOVA by ranks ($F_r = 17.17$, $p < 0.01$). Post hoc comparisons show that the differences in overall workload were significant between the basic and the predictor displays ($p < 0.05$) and highly significant between the basic and the advisor displays ($p < 0.01$). No significant differences were found between the predictor and the advisor displays.

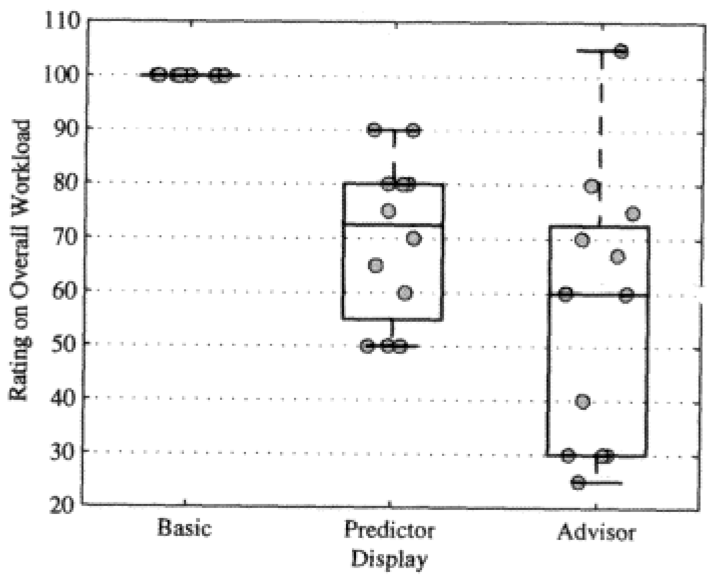


Figure 3-6. Overall Workload.

Subjects' preference rankings of the displays were also significantly different for the three displays (Friedman two-way ANOVA by ranks, $F_r = 17.17$, $k = 3$, $N = 12$, $p < 0.01$). The advisor display was the most preferred display—75% (9 of 12) of subjects preferred the advisor display to the other two displays, while 25% (3 of 12) preferred the predictor display. The least preferred display was the basic display—92% (11 of 12) of subjects disliked the basic display, while 8% (1 of 12) disliked the predictor display. Note that no subject preferred the basic display as his or her first choice or the advisor display as the last choice. Post hoc comparisons reveal 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 ($p = 0.12$).

3.5 LEARNING CURVES

Performance data collected during training are presented in Figure 3-7. With aiding, no speed violation occurred on any training run; without aiding, subjects were able to remain within the tolerance of speed violation (less than 45 meters) only after a full set of training runs. Ride quality, as measured by the number of jerks, 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 with the corresponding displays. Nevertheless, the number of training practices was not found to affect the five performance measures by a two-way ANOVA. The reason that little learning can be perceived from the training data is explained in the section 4.2.7.

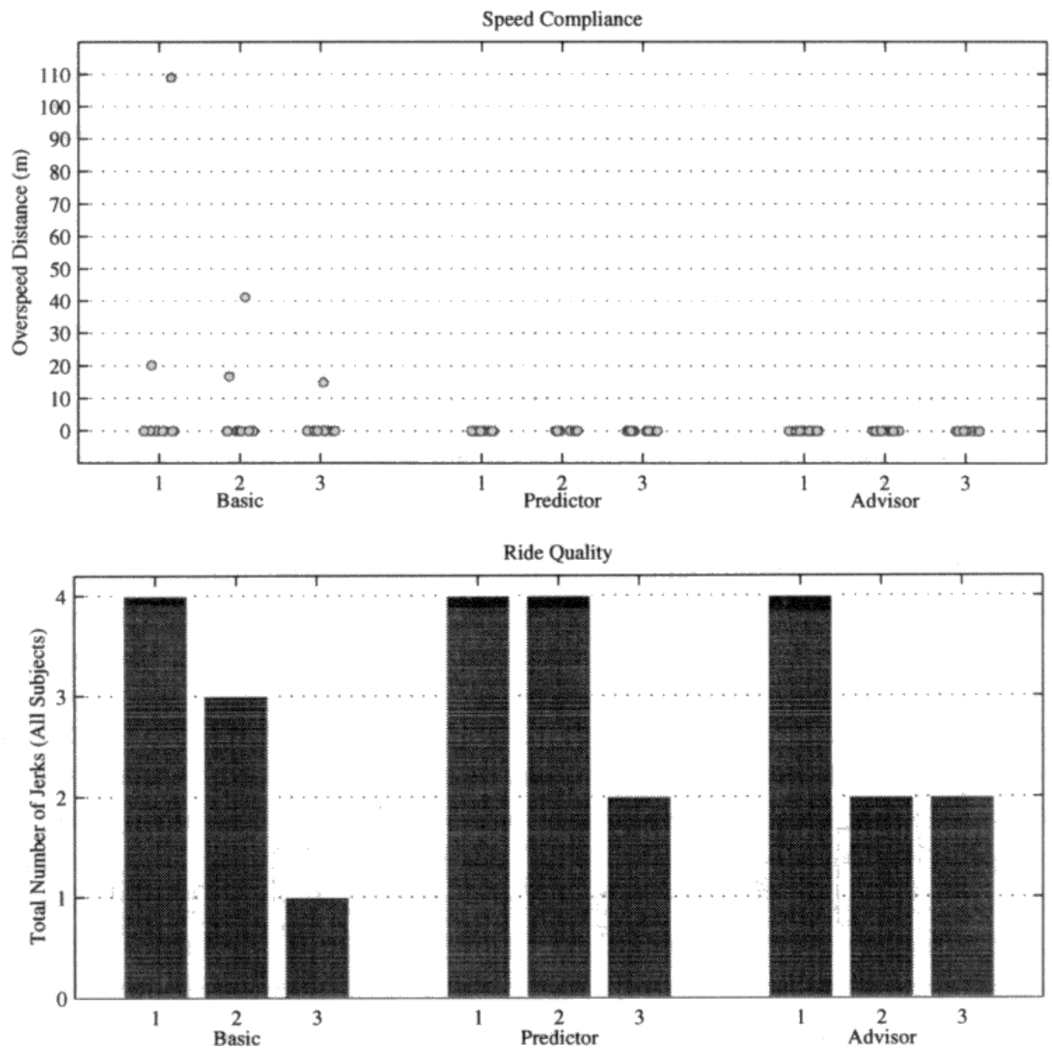


Figure 3-7. Performance During Training (Continued on next page).

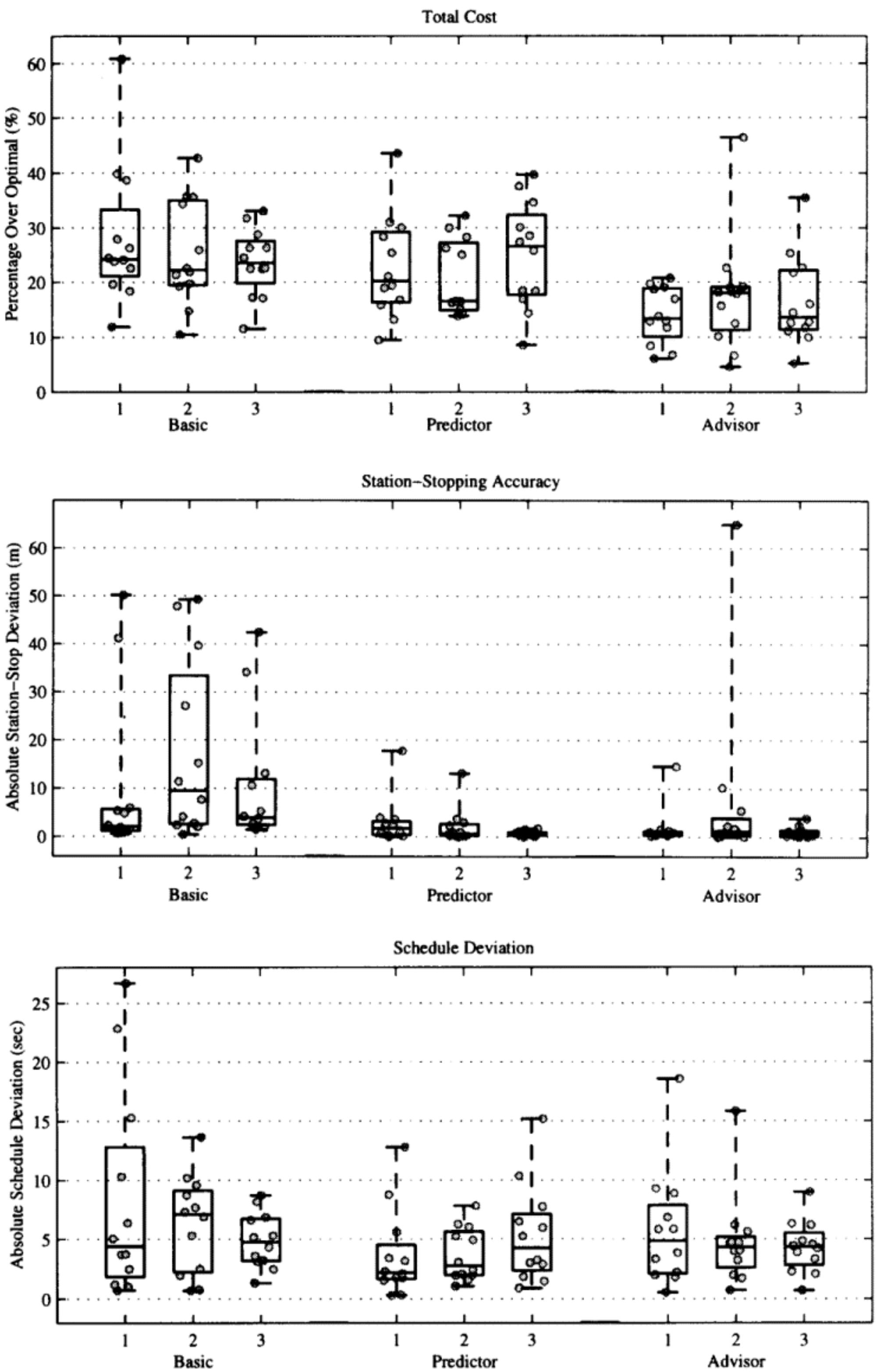


Figure 3-7. Performance During Training. (Cont.)

4. DISCUSSION

4.1 SUMMARY OF RESULTS

With the predictor and the advisor displays, subjects performed equally well in several safety-related measures. Under the emergency scenario, both displays significantly reduced the time of reaction to an unexpected signal event from a mean value of 8.6 to 1.4 seconds and reduced red-light overruns from 17% to 0%. They also significantly reduced mean station-stop deviation from 12.7 meters to under 1 meter.

The advisor display showed advantages over both the predictor and the basic displays in total cost (that of energy consumption plus a weighted schedule deviation) and schedule adherence. The advisor display significantly reduced total cost by 11% over the basic display, and significantly shortened mean schedule deviation from 11.1 seconds with the basic display to 3.8 seconds. In comparison, the predictor display had a trend to reduce both total cost and schedule deviation over the basic display (0.05 p 0.1). No significance differences were found in total cost or in schedule deviation between the predictor and the advisor displays.

For routine speed control and emergency handling, the mean rating on time pressure with the basic display was the highest among the three displays. This difference, however, was not found to be significant. Ratings on mental effort and stress with the advanced displays were significantly lower (with the advisor display) or showed a trend to be lower (with the predictor display) than those with the basic display for both routine speed control and emergency handling.

For speed control with the secondary task, ratings on time pressure and mental effort were not significantly affected by the displays. Stress was rated significantly lower for the predictor display than that for the basic display.

In spite of the concern that increased aiding might induce higher visual workload, several measures indicated that such a concern was unjustified. Spare visual capacity (tracking error in the secondary task) and ride quality were not significantly different across displays. Moreover, subjective ratings on time pressure, mental effort, and stress for the advanced displays were lower than those for the basic display for both routine speed control and emergency handling. A retrospective and relative questionnaire also revealed a significant decrement of overall workload with the increase in display aiding. Further, there was a significant preference for the advanced displays over the basic display: the higher the display level (progressing from the basic to the advisor display), the more it was liked by the subjects.

4.2 INTERPRETATION

4.2.1 Situation Awareness

The significant reduction in mean reaction time to unexpected events demonstrates that, as expected, the advanced displays can improve the locomotive engineer's situation awareness by extending their capability of looking ahead for signals (Hendy, 1995). This reduction in reaction times could be attributed to the preview aiding present in the advanced displays and may be explained as below. First, the prominent change in the pattern of signal aspects in the advanced displays at the onset of a signal event was a major factor. The preview aiding provided salient sensory stimulation not only by presenting multiple blocks of signals simultaneously but also by introducing an additional aspect of the signal—the vertical position of the signal. Second, the attention shift from outside window to inside the cab with the advanced displays may have contributed to the reduction of reaction times. With the advanced displays, subjects mostly looked at the displays, seldom "out the window." More attention to the displays would naturally increase chances of rapid detection of a signal change.

One may argue that the reduction of reaction times was due also to the predictive aiding that reduced subjects' time to decide between full-service and emergency braking. Subjects were trained, however, to apply the full-service brake immediately after detecting the emergency signal event, before deciding on whether and when the emergency brake should be applied. The choice time should thus not be present in the reaction time if subjects followed instructions. Another indication that preview was the main factor in reducing reaction times was their bi-modal distribution. Seven out of the twelve subjects reacted to the signal change in less than 3.8 seconds, presumably because their attention was on the display at the onset of the signal event. The remainder of the subjects (5 of the 12) took more than 8.2 seconds, presumably because their attention was on the outside view when the signal change occurred. In comparison, with the advanced displays all subjects responded to the event in less than 2.9 seconds because their attention was mostly on the displays. Therefore, it was visual attention, and not decision-making, that was responsible for the reaction time differences, and it was the preview aiding, and not the predictive aiding, that was the key factor for the reduction of reaction times.

4.2.2 Quality of Decision Making

The predictive aiding played an important role in improving the quality of decision making in both routine speed control and emergency handling. It enabled the subjects to make informed control decisions in normal operations. In particular, the predicted speed curves helped the subjects to avoid both costly excessive braking and speed infraction. The handling of the emergencies strongly indicates that the advanced displays can also improve the locomotive engineers' decision making under the emergency condition. Because the emergency braking curve explicitly indicated the "last moment" or "point of no return," subjects could choose the appropriate braking mechanism and initiate emergency braking, when necessary, at the lowest possible speed without jeopardizing safety. With no predictive aiding, subjects were confronted with estimating the "critical moment" based on their experience alone.

4.2.3 Speed Compliance

No speed violations were committed in any of the conditions. This shows that subjects were well trained and had no bias favoring the advanced displays. It is unlikely that a well-trained locomotive engineer (familiar with the dynamic behavior of the train and physical characteristics of the route) would commit a speed violation over a 30-km run. The short test course and the relatively small number of subjects (12) may not be enough to show effects of these aids on speed compliance. Therefore, to observe differences in speed compliance among the three displays, subjects would have to be tested over a longer, fatigue-inducing test course.

4.2.4 Operational Efficiency

Both advanced displays have potential in improving schedule and station-stop performance. 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 them approach the station with assurance and relative ease. Similarly, the predictive aiding improved schedule adherence by helping subjects to avoid excessive braking.

Ride quality appeared to degrade with the increase in aiding level. Combining the number of jerks induced by all subjects in both routine speed control and the secondary task conditions shows over twice as many total jerks with the predictor or the advisor display as with the basic display. Nevertheless, no significant effects of the displays on ride quality were found when combining the data from the routine speed control with those under the secondary task condition (Cochran Q test, $Q = 2.25$, $df = 2$, $p = 0.47$). Although ride quality was not shown to suffer significantly with the increase in display level, the tendency of more jerks with higher level of displays deserves further investigation.

As for the total cost, the advisor display was able to help keep the total cost closest to the minimum. On real tracks, where the speed limits and track geometry are more varied, the reduction of total cost by the advisor display with respect to the basic display is expected to be greater than that demonstrated in this experiment (11%).

It should be noted that, in practice, it is unrealistic to expect a train to follow the optimal speed profile even if the locomotive engineer were to follow 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 resistant forces. The resistant force in the model may not be able to 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.

Owing to the relatively long computation time involved in obtaining an accurate optimal speed profile, however, this research was restricted to presenting an optimal profile for the whole trip without updates, and studied the behavior of the locomotive engineer under such aiding. The authors believe that the lack of dynamic updating of the optimal profile did not affect the results on use of such an advisory aid because (1) it was relatively easy for the locomotive engineer to follow the advisor because of the slow train dynamics and the presence of predictive aiding, and (2) even if updating were allowed, it would have been assumed that the updating was "fast enough" and the locomotive engineer would not perceive the difference between old and new advisors.

4.2.5 Workload

Ratings of time pressure were not significantly affected by the displays in any of the three types of test runs. This was expected, because during the runs of routine speed control and emergency handling, subjects did not have overlapping activities; and during the runs of speed control with the secondary task, subjects were constantly occupied by either the speed control or the secondary tracking task while using any of the displays.

Subjects thought that the predictor and the advisor displays were significantly less mentally-demanding than the basic display for both routine speed control and emergency handling, but not for speed control with the secondary task. The advanced displays relieved the subjects from mentally estimating braking curves and extrapolating future speed response, and relieved them from intensely searching for landmarks and signals in the fast-flowing visual field. As a result, low mental demand was involved in the speed control task with the advanced displays.

The unexpected lack of significant effects of the displays on mental effort for runs of speed control with the secondary task may be explained by the dependencies between mental effort and time pressure. With the presence of the secondary task, subjects felt more attention competition while using the advanced displays as a result of having more information for them to attend. Although such competition of visual attention was not significant, as the secondary task was shown to be non-intrusive, it left subjects less time to keep track of details of the advanced displays and the 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 ratings of mental effort insensitive to displays.

As expected, subjects thought that the advisor display significantly lowered their stress level than the basic display for routine speed control and emergency handling. 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 may have created stress. For speed control with the secondary task, however, subjects perceived that the predictor display, and not the advisor display, was significantly less stressful than the basic display. This may be explained by the difficulties involved in performing two tracking tasks at the same time. Among the three displays, the advisor display demanded the most attention because subjects had to follow the optimal profile closely, in addition to performing the secondary tracking task.

These results of subjective ratings must be viewed with caution, however. Studies have shown that subjective ratings via an immediate-absolute method are usually correlated with the subjects' performance in the particular run just completed, and thus can be biased (Tsang and Vidulick, 1994). (Hence the retrospective and relative measures of subjective workload were also assessed in this research.) In fact, the retrospective and relative questionnaire did reveal significant decrement of overall workload with the increase in display aiding.

Subjects' comments in the post-experiment 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 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, although being the most preferred by 9 of the 12 subjects, 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 of the twelve 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...."

4.2.6 Potential Overload

One might argue that although the increased head-down time with the advanced displays was a positive factor in signal detection and fast reaction to unexpected events, the increased head-down time implies that this advantage may come at a cost of attention to tasks other than speed control. The following facts, however, indicate that there is insufficient evidence to draw the above conclusion. First, the relatively larger number of peak tracking errors and the larger number of jerks with the advanced displays than with the basic display were not found to be statistically significant. Second, the advisor display had strong appeal to the subjects. In fact, subjective ratings from an immediate-absolute technique showed that the advisor display had the lowest workload among the three displays for routine speed control and emergency handling. In addition, subjective ratings from a retrospective-relative technique showed significant effects of the displays on overall workload. Moreover, most of the subjects chose the advisor display as their first choice.

In fact, an increase in head-down time (or shift of attention to inside the cab) with the advisor display was necessary and expected. With the advisor display, the necessary information for speed control was shifted from outside to inside the cab, which eliminated or reduced the need of looking out of the window for important signals. As a result, the out-the-window view may not be needed for information acquisition by the locomotive engineer, and one may wonder about the utility of the cab windows. After all, without cab windows, locomotive engineers can avoid visual overload induced by involuntary subjection to a fast-flowing visual field. But whether to totally eliminate cab windows under a comprehensive advisor display remains an open question. The windows may have to exist for psychological satisfaction if not for operational requirements.

That the increased head-down time contributed to the improved situation awareness in train operations seems contradictory to what is associated with head-down time in aviation. An airplane pilot can change the plane's flight path immediately upon the discovery of an object ahead. Looking out-the-window helps the pilot not only to discover the object, but also to choose an appropriate direction of maneuver. A train, however, does not have the degrees of freedom that a plane does, and thus stopping the train by applying emergency braking is all a locomotive engineer can do to avoid a collision. Since the presence of an object ahead of a train can be reflected by the signals that prevent the following train from approaching the object-occupied block, head-down time would not pose as great a threat to safety for train operation as for flying an airplane so long as the signals are presented to the locomotive engineer inside the cab.

4.2.7 Effects of Displays on Training

The reason that subjects did not seem to experience significant learning during the training is provided as follows. Subjects were trained 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 amount of coaching was kept 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. Therefore, the learning was actually stronger than that found by the statistical analysis.

In fact, the trend of reduced distance of overspeeding with increasing practice runs while using the basic display, indicates that subjects experienced learning in speed compliance. With the advanced displays, in contrast, no overspeeding was committed by any subject in any practice run, implying that the advanced displays may have an inherent tendency for better speed compliance than the basic display.

In summary, the advanced displays appear to allow a novice better performance in speed compliance, total cost, schedule adherence, and station-stopping accuracy than the basic display. This indicates that the time needed to train a novice to a given level of performance with the advanced displays, would be much shorter than that with the basic display.

5. EVALUATION VIA SIMULATION WITH A HUMAN MODEL

5.1 INTRODUCTION

Evaluation of safety-critical and capital-intensive human-machine systems such as locomotive engineer-cab systems can be done with two methods: human-in-the-loop experiments and simulation with a human model. The former are often complex and difficult to design and control. One difficulty is the determination of which parameters should be held constant, which should be varied, and over what range. A second difficulty is that a large number of trials is needed because of the variability introduced by individual differences which might obscure the effects of experimental manipulations. In addition, the use of human subjects in an experiment requires considerable training, and economic constraints preclude the execution of a large number of trials. Consequently, a human-in-the-loop evaluation study can become large and very time-consuming.

The method of model-in-the-loop simulation for evaluating a human-machine system, in comparison, provides flexibility in analyzing the effects of design parameters on system performance. It allows evaluation of a new design to be achieved in shorter time and at a lower cost once a suitable human model is available. The disadvantage with such a method, however, is the difficulty involved in developing the human model.

This chapter describes the locomotive engineer model developed as a tool to evaluate decision aids proposed for future high-speed trains, and presents an application of the model that extends the experimental results reported in the previous chapters. In particular, model-in-the-loop simulation was conducted to predict the locomotive engineer’s responses to a dynamic signal event, wherein changes in the signal were induced by a moving lead train (as opposed to the unexpected stationary object in the human-in-the-loop experiment).

5.2 ANALYSIS OF DRIVING BEHAVIOR

To develop a high-speed train locomotive engineer model, the nature of the driving task was first analyzed. A train's speed on a block signaling system is governed by stepwise speed limits and signals along the track, and can be manipulated by the locomotive engineer via application of braking or propulsive force. (Under a block signaling system, a track is divided into segments or blocks with each having a signal fixed at the entrance of the block or displayed inside the cab or both.) In train 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 to control the train's speed under the constraints of speed limits and signals—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. Because of the train's huge inertia, train speed control requires significant anticipation.

This driving behavior can be characterized with the model in Figure 5-1. Functionally, there are two major sources of input to the locomotive engineer: present and future command information, and immediate feedback information. The former contains signals, obstacles, and so on, that are to be detected and interpreted correctly and in a timely manner in order to form a *target state*, i.e., the desired speed at a particular location ahead (V_{target} and X_{target} in Figure 5-1). 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 type of driving behavior holds mainly for vehicles in surface traffic and for airplanes during take-off and landing (Mashour, 1974).

The meaning of "target state" in the context of train driving may be explained as follows: on an open track, the speed limits and signals are commands that govern the train's output variables, the speed and the location of the train. The locomotive engineer is expected to control the train such that before, rather than after, entering the next block, its speed should be within the speed limit of the new block. Therefore, the locomotive engineer needs to know the distance to and the amount of the next speed reduction in order to initiate braking in time. Getting such information requires the locomotive engineer to look ahead—to preview, i.e., to continuously scan the field of view in search of future inputs in order to the make current control decision. The future inputs, be they signals or dangerous situations, are transformed by the locomotive engineer into a corresponding short-term target state which consists of a desired speed at a near future location. The target speed at the future position on the track is the reference input for guiding the current application of control force.

To achieve the target state, the locomotive engineer constantly predicts the potential of reaching the target state under current force application and adjusts it according to control decision-making rules or experience with train handling and track geometry. The immediate feedback information shown in Figure 5-1 is the most significant feedback indicator for controlling the speed of the train.

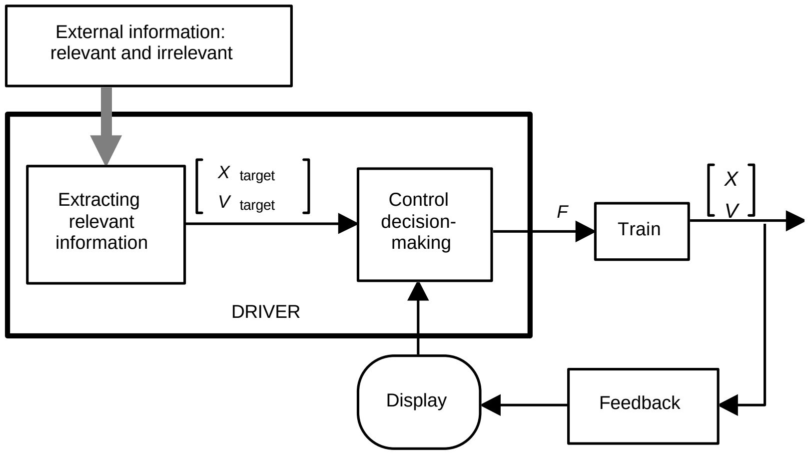


Figure 5-1. Model of Information Flow in Locomotive Engineer-Cab Systems. *X*—position of train. *V*—speed of train. *F*—propulsive or braking force.

5.3 Overview of the Locomotive Engineer Model

There are two types of human models: a *normative* model, which prescribes 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 model of the locomotive engineer that was a combination of the normative and descriptive notions. It was normative because it was based on the rules used in training the subjects for the experimental tests. It was descriptive because one parameter in the human model, i.e., the reaction time to an unexpected signal, was determined from the human-in-the-loop experimental results described in Chapter 3.

The reason behind the choice of a rule-based model was fourfold. First, the necessary preview behavior in train operation precludes the use of the well-studied linear feedback control models (McRuer et al., 1965; Baron and Kleinman, 1969; Baron and Levison, 1975, 1977; Wewerinke and Tak, 1988; Levison, 1993). The conventional feedback controller operates on instantaneous error between current input (e.g., speed limit) and actual measured output (e.g., speed) and has no way of taking into account its immediate future input, such as the next speed limit along the route for a train. Second, the locomotive engineer's knowledge obtained from training, e.g., route characteristics, could not be naturally incorporated into non-rule-based models such as those studied by Sheridan (Sheridan, 1966). Third, the relatively few driving rules are simple compared to the more complicated dynamic system operations characteristic of, for example, airplanes. Fourth, rule-based modeling easily allows accommodation of the nonlinear and time-varying dynamics of the train.

5.3.1 Assumptions of the Model

Major assumptions underlying the locomotive engineer model are as follows: (1) The locomotive engineer is sufficiently well-trained and motivated to perform in a near optimal manner, subject to system goals and limitations. (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 the signal. (3) The task of the alert system can be neglected in the model. 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.

5.3.2 Structure of the Model

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 5-2. The optimal model is a direct implementation of the optimal control solution whose corresponding optimal speed profile was used in the advisor display. The optimal model assumes that the locomotive engineer is trained to operate the train by proper manipulation of the throttle to produce the optimal speed control for the trip. However, the optimal strategy may become unavailable because an emergency maneuver *en route* forces the train to deviate from the optimal trajectory and, as a result, the rest of the previously optimal strategy becomes no longer optimal. The inaccuracy of the dynamic model used to obtain the optimal control strategy, may also lead to gradual deviation of the train from the optimal trajectory, even if the locomotive engineer followed the optimal strategy precisely. A remedy for this could be the 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 a continuous update of the optimal trajectory under dynamic situations such as those created by an unexpected lead moving train. Upon the invalidation of the optimal control rules that the locomotive engineer has relied on in routine operations, he or she would resort to a survival strategy which is modeled by the max-max strategy. The max-max model was implemented as a set of control rules the locomotive engineer must use when the optimal control strategy becomes unavailable.

The max-max control strategy can be summarized simply by the following rule: apply maximum propulsion when an acceleration is called for, or maximum braking when a deceleration is called for; otherwise, cruise with a force just balancing the friction. The rate of application of the propulsion or braking must be subject to consideration of ride quality, i.e., the rate of acceleration or deceleration or the train should be within a tolerance.

Decision-making with this rule involves using the knowledge or experience a locomotive engineer has learned during training and previous journeys. Four functional components of the knowledge base are depicted in Figure 5-2, 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 locomotive engineer's skill at throttle manipulation under the constraint of ride quality. The *route characteristics* are track geometry and major points along the route that are associated with important control actions. The *schedule* is used to compensate for schedule deviation.

It should be noted that the out-the-window view is not explicitly shown as a source of information to the locomotive engineer in Figure 5-2. The model recognizes the use of an outside view mainly as cues (landmarks) associated with control maneuvers, and therefore the function of the outside view to the locomotive engineer has been considered as part of the knowledge base of route characteristics.

The perception block in Figure 5-2 represents the process of a locomotive engineer's extracting meaningful information from the displays. An important question in developing such a model is what the locomotive engineer perceives from a given indicator. For a numerical (digital) indicator such as that of the current speed (simple value at any time instant), it is assumed that perception is just a read out 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 a direct reading of the values of the indicators.

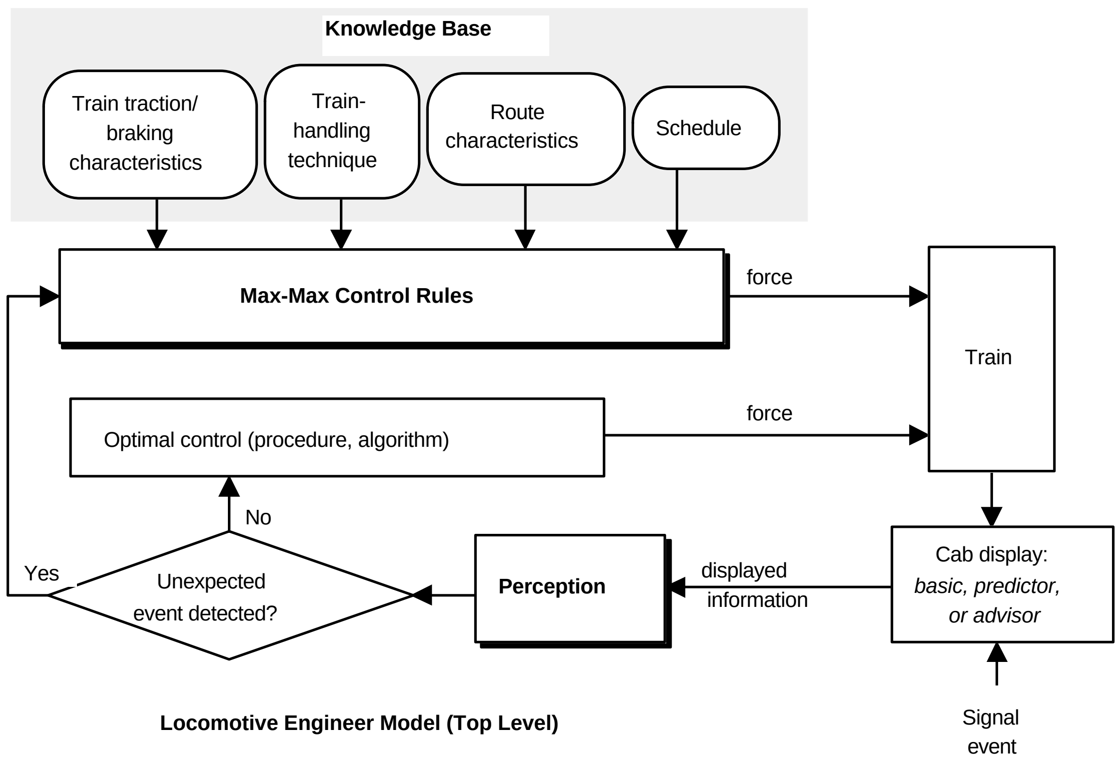


Figure 5-2. Integration of Two Control Strategies in the Locomotive Engineer Model. The blocks with a heavy frame (▢) are functions whose lower level decompositions can be found in Appendix O.

A different treatment is needed, however, for modeling the perception of a continuous range of graphically displayed information (multiple values at any time instant). 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 locomotive engineer extracts the location and the level of speed reduction in the preview range, as illustrated in Figure 5-3. (Subjects were in fact trained to use the aid in such a manner in the experiment described earlier.) The rationale behind this assumption is that speed reductions require advance attention to initiate braking in time to reduce speed to the next block's limit before reaching that block. Therefore, speed reductions paired with the distances to the points of speed reductions, e.g., $X_{reduction,1}$ and $V_{reduction,1}$ in Figure 5-3, are extracted from the profiles of the speed limit and the signal in the preview range.

These pairs of distances and amount of speed reductions are used, in turn, to extract the braking distances from the current speed to the reduced speed levels in the preview range. Thus, the decision as to whether braking is needed at any moment can be reached by evaluating the differences between the distances to the points of speed reductions and the corresponding braking distances, e.g., $D_{braking,1}$ and $D_{braking,2}$ in Figure 5-3. Therefore, only crucial pieces of information are extracted by the locomotive engineer from the full-service braking curve during the perception process.

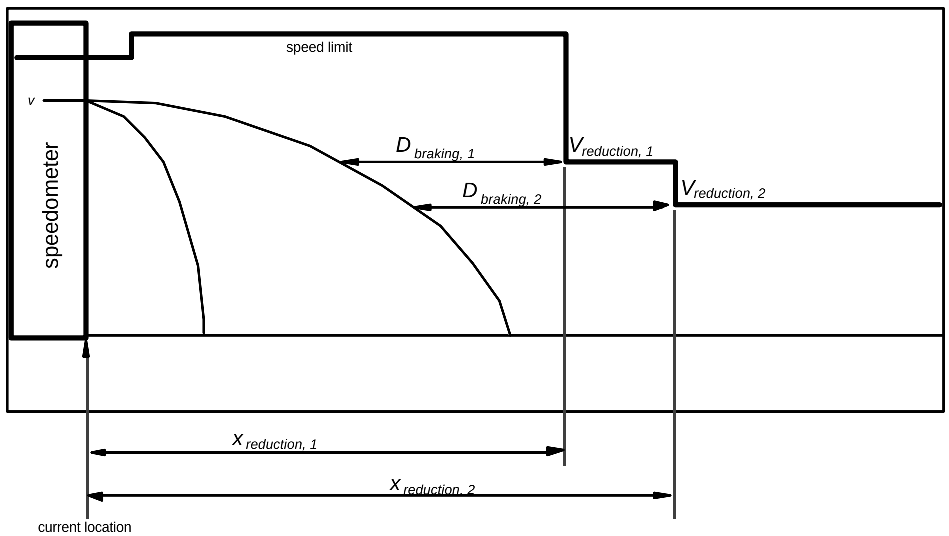


Figure 5-3. Extraction of Relevant Information From Speed Limit Profile and Predictor Curves. Only amounts of speed reductions and corresponding locations are extracted from the previewed speed limit profile. Full-service braking distances to the locations of speed reduction are also extracted.

5.3.3 Implementation of the Model

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 simulator was capable of both fast-time simulation with the locomotive engineer model and real-time human-in-the-loop simulation. The implementation of the model was flexible because signal events could be flexibly configured and tested with different command-line input parameters, and the parameter of human operator limitation in detection of signals could be easily varied. These features made the model a useful tool for predicting the effects of operator-related parameters on performance.

5.4 APPLICATION

5.4.1 Scenario

The model was applied to extend the findings of human-in-the-loop experiments. Effects of the displays on safety were investigated, during a dynamic event wherein the signals were activated by a lead moving train instead of by a stationery object. The scenario was as follows: the train started with the optimal control strategy along a straight and flat test course of 30 kilometers (Figure 2-4). When it reached kilometer post 14.6 (KP14.6) with a speed of 250 km/h (on the optimal trajectory) and an acceleration with 90% of full propulsive force, 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") occurred. The signal change was activated by a leading train that suddenly appeared at KP 22 (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 slowed down to 70 km/h when reaching KP 27.2 and maintained the speed of 70 km/h.

The following train, i.e., the train governed by the locomotive engineer model, reacted to the events only after perceiving the signal change. The times of reaction to such an event were measured from the human-in-the-loop experiment: a mean value of 8.6 seconds for the basic display and 1.4 seconds for the advanced displays (i.e., the predictor and the advisor displays). These mean reaction times were used as the delay in the perception of a signal change—the only time delay considered in the perception component of the model.

5.4.2 Results

Figure 5-4 compares the responses of the model with the basic display and the advanced displays during the dynamic signal event described above. In particular, when comparing responses around KP 14.6 (when signal change occurred) between the basic and the advanced displays, we can observe that, with the basic display, the "locomotive engineer" 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 via the *automatic train protection* (ATP) system. In contrast, with the predictor or the advisor display, the "locomotive engineer" 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.

Operation under the predictor or advisor display could also bring about benefits in operational efficiency. By avoiding the emergency braking, the locomotive engineer with the advanced display could spend less energy than with the basic display because he or she could avoid the energy-consuming process of accelerating the train to a safe operational speed. In addition, the advanced displays could greatly reduce the delay in arrival time as a result of being able to avoid unnecessary emergency braking.

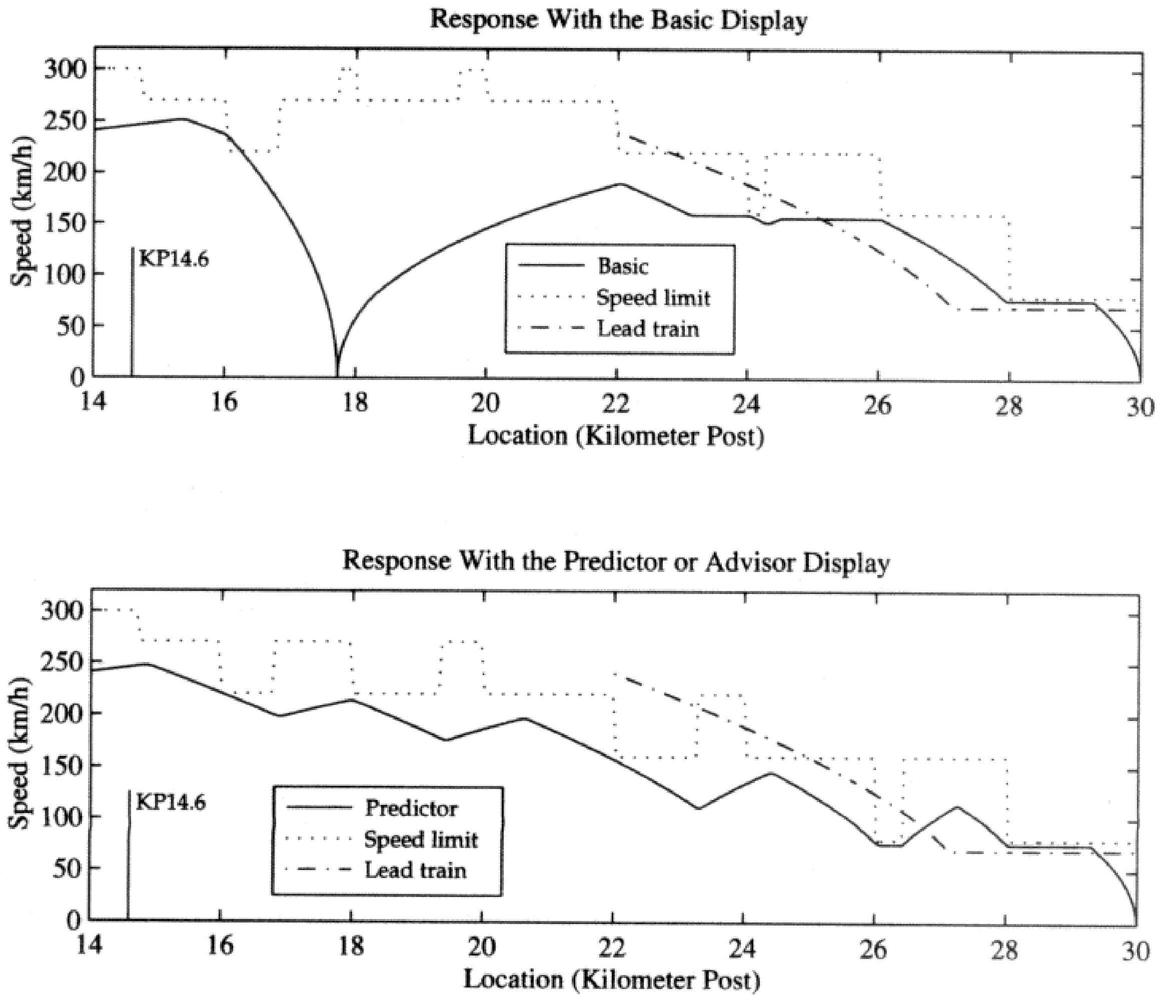


Figure 5-4. Responses to Dynamic Signal Event by Model with the Basic and the Predictor Displays.

5.5 CONCLUSIONS

The investigation by simulation with a locomotive engineer model shows that the predictor and the advisor displays are capable of improving safety in terms of speed compliance and timely response to unexpected signal events. The model-in-the-loop simulation results support the finding of the human-in-the-loop experiments in that the advanced displays offer not only increased safety, but also reduced emergency braking which would reduce injuries to passengers or damage to equipment, and result in shorter delays in schedule and less energy consumption.

6. RECOMMENDATIONS AND FUTURE WORK

In view of the above results and discussion, some recommendations can be offered.

First, the results of this investigation suggest that the advisor display used in this study (including both preview and predictive aiding) is a promising level of aiding. Although the display tends to shift the locomotive engineer's attention from outside the window to inside the cab, the shift of attention may not be a concern if all important or necessary information is provided inside the cab, especially during high-speed *en route* operations.

Before putting the advisor display into service, more research is needed to take advantage of the proposed aids while eliminating any potential negative effects. The divergence between the objective (via secondary task performance) and the subjective measures of workload found in this research, although not significant, shows the importance of such an investigation. For example, different methods of workload measurement may be necessary to obtain further insights on workload associated with the proposed displays. Further, an experiment with professional locomotive engineers would be able to provide more insight on the use of and potential improvement of the proposed aids.

Second, practical issues associated with implementing the advisor display on a high-speed train include: (1) What on-board computing capability is required to allow updates of the optimal speed profile *en route* (note that the present research was restricted to presenting an optimal profile for the whole trip before departure and without *en route* updates)? (2) How accurate should the optimal profile be in order to retain the benefit of cost saving? (3) How should the previewed signals be transmitted into the cab in order to display them in the advanced displays?

Third, as mentioned in the introduction, there are two options in aiding the locomotive engineer: more decision aids like those presented in this research, or more automation. Although the direction of this research has been in decision aiding, maybe a combination of the decision aids presented here with some automation could be a better locomotive engineer-cab system design. For example, since station stopping was found to be significantly more demanding of visual attention than *en route* control, it may be worth investigating automated station stopping (e.g., programmed stopping) in connection with the use of the advisor display.

REFERENCES

B&P Videoproduktion. (1992). *The safe journey*. Produced for Swedish National Rail Administration.

Baron, S. and D. L. Kleinman. (1969). "The human as an optimal controller and information processor," *IEEE Trans. on Man-Machine Systems*. MMS-10, No. 1, pp. 9-17.

Baron, Sheldon and William H. Levison. (1975). "An optimal control methodology for analyzing the effects of display parameters on performance and workload in manual flight control," *IEEE Trans. on Systems, Man, and Cybernetics*. SMC-5, No. 4, July. pp. 423-430.

Baron, Sheldon and William H. Levison. (1977). "Display analysis with the optimal control model of the human operator," *Human Factors* 19 (5), pp. 437-457.

Bellman, E. Richard and Stuart E. Dreyfus. (1962). *Applied dynamic programming*. Princeton University Press.

DOT/FRA (U. S. Department of Transportation/Federal Railroad Administration). (1991). *Safety Relevant Observations on the TGV High Speed Train*. July.

Endsley, Mica R. (1993). “Situation awareness in dynamic human decision making: Measurement,” *Proceedings of the First Intl. Conf. on Situational Awareness in Complex Systems*. Orlando, Florida. February.

Endsley, Mica R. and E. O. Kiris. (1995). "The out-of-the-loop performance problem and level of control in automation," *Human Factors*. 37(2): 381-394.

Gruère, Yves. (1992). *Proceedings of Canada France Symposium: TGV System Developments*. National Arts Center, Ottawa. March 25-26. pp. 87-98.

Hendy, K. C. (1995). Situation awareness and workload: birds of a feather? *AGARD AMP Symposium on “situational awareness: limitations and enhancements in the aviation environment.”* Brussels. April 24-28.

Levison William H. (1993). "A simulation model for the driver’s use of in-vehicle information systems," *Proc. of Transportation Research Board 1993* Annual Meeting.

Luedeke, Jonathan F. (1992*). Glossary of terms for the program National Methodology for Safety Validation of Computer Controlled Subsystems Used in Guided Ground Transportation Systems*. Interim report to Volpe National Transportation Systems Center. December 12.

Mashour, M. (1973). *Human factors in signaling systems: Specific applications to railway signaling*. Stockholm: Almqvist & Wiksell International. New York and Toronto: John Wiley & Sons.

McRuer, D., D. Graham, E. Krendel and E. Reisener, Jr. (1965). *Human pilot dynamics in compensatory systems — Theory models and experiments with controlled element and forcing function variations.* AFFDL-TR-65-15, Wright-Patterson ATB.

O'Donnell, R. D. and F. T. Eggemeier Workload assessment technology. *Handbook of perception and human performance: Volume II. Cognitive processes and performance*. K. R. Boff, L Kaufman, and J. Thomas (eds), Chapter 2. New York: John Wiley and Sons.

Petit, Georges. (1991). "The Atlantic TGV, Mastering the speed of 300 km/h," English translation of the special issue of *Revue générale des chemins de Fer* (published in October): 27-33.

Shavelson, R. J. (1988). *Statistical Reasoning for the Behavioral Sciences* (2nd edition). Boston and London: Allyn and Bacon, Inc.

Sheridan, T. B., and Ferrell. W. (1974). *Man-machine systems*. Cambridge, Massachusetts: Massachusetts Institute of Technology Press.

Sheridan, Thomas B., Edward Lanzilotta, and Shumei Y. Askey. (1994). *Safety of high speed guided ground transportation systems, Phase I: Human Factors.* Final Report to DOT/FRA (U. S. Department of Transportation/Federal Railroad Administration). October.

Siegel, Sydney and N. John Castellan, Jr. (1988). *Nonparametric statistics for the behavioral sciences* (second edition). New York and St. Louis: McGraw-Hill, Inc.

Tsang, Pamela S. and Michael A. Vidulich. (1994). "The roles of immediacy and redundancy in relative subjective workload assessment," *Human Factors*. 36(3): 503-513.

Wewerinke P. H. and C. van der Tak. (1988). "Model of the human observer and controller of a dynamic system: Theory and model application to ship handling," *Proceedings of IFAC Man-Machine Systems*. Oulu, Finland, pp. 163-168.

Ziebolz, H. and H. M. Paynter. (1954). "Possibilities for a two-time-scale system for control and simulation of dynamic systems," *Proc. National Electronics Conference* (9), pp. 215-223.

APPENDIX A

RESULTS SUMMARY AND DISCUSSION OF THE PRELIMINARY EXPERIMENT

A.1 INTRODUCTION

The preliminary experiment was conducted to evaluate the effects of preview aiding on locomotive engineers' performance. Two levels of cab information displays were comparatively studied through the preliminary human-in-the-loop experiment: one, referred to as the *basic display*, consisted of the standard signal indications inside a cab; the other, referred to as the *preview display*, showed not only the indicators provided in the basic display, but also previews of stopping distances, speed limits, signal aspects, track topology, and so on.

The preview display was expected to allow subjects to have better situation awareness and decreased workload. Operator performance in station stopping, schedule adherence, and ride quality were also expected to improve with the preview display as compared to with the basic display. Subjects' ability to operate the train was expected to decrease after a failure of the information aids (preview failure).

No out-the-window view was used in the preliminary experiment. The implies that some performance measures may need further investigation when the out-the-window view is available (as in the main experiment described in this report).

A.2 OVERVIEW OF SIMULATED ENGINEER-CAB INTERFACES

Three input devices were used in the engineer-cab interface simulation for the preliminary experiment: keyboard, mouse, and a dual-use throttle. The throttle was programmed to be capable of applying both braking and traction, with each function allocated one half of the throttle throw. It also had a center notch to provide tactile feedback on its functional position (braking vs. traction). To provide a baseline for studying levels of display aiding, subjects were provided with a manual control mechanism only.

Instruments and indicators in a simulated cab environment with the basic display, shown in Figure A-1, included 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, indicated current speed (item 1 in Figure A-1), speed limit of the current block (item 2), and speed limit of the next block (item 3). To the upper right of the speedometer was the cab signal consisting of three colored lights (item 4). Each of the lights might 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 was provided below the speedometer. The grade (in degrees) of the track at the current location (item 7) was shown under the speedometer. The number of the block where the train was currently located and the number of the kilometer-post that the train had just passed, were shown below the lower right corner of the speedometer with the symbols BL followed by the block number (item 6) and KP followed by kilometer post number (item 5). In addition, the distance to the next station (item 9) was displayed to the lower right of the block number (outside the frame of the central region). Under the distance to the next station was the current time (item 10).

The indicator corresponding to the dual-use throttle was a horizontal grid bar located under the frame of the central region in Figure A-1 (item 8). The center grid of this indicator corresponded to the center notch position of the throttle. Functionally, this position of the throttle is neutral; no braking or traction was applied. To the left of the center grid, braking was displayed; to the right, traction level. The throttle was capable of continuous force application (as compared to notched levels) and its force level was displayed accordingly. The grid lines on the force indicator were provided as measures of force level at every 10% of the maximum available braking or traction.

Functions related to speed control were provided on the right side of the screen of the cab display simulation computer. Two functions were shown in Figure A-1: the automatic train protection (ATP) system and the emergency stop (ESTOP). The emergency stop could be activated manually via a mouse-click on the emergency-stop indicator. The ATP system warned the locomotive engineer (by blinking its triangular indicator) when the speed of the train was above the speed limit. It would automatically activate the emergency stop when (1) the train was excessively overspeed—more than 15 km/h above the speed limit, or (2) the speed of the train was in the warning zone (within the 15 km/h overspeed tolerance) for more than 20 seconds. Emergency braking, whether activated manually or automatically, could not be reset until the train has fully stopped.

To the lower left of the speedometer (outside the central region) was 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 was not moving. Conversely, the train could not move unless the door had been closed.

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

A call-up schedule display was provided at the lower left of the workstation screen. The schedule, which could be shown or hidden by a mouse-click on the *schedule* button, consisted 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 were the incoming and outgoing message areas. The in-coming messages from the dispatcher at the Central Traffic Control were displayed in the *CTC MSG:* area, with the most recent message at the bottom. (Note: other messages are scrolled upward). The locomotive engineer could 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).

Status of other onboard subsystems were displayed on the right side of the workstation screen, such as braking pipe pressure, tank pressure, etc. They were not used in this experiment.

Figure A-2 shows the preview display which presented additional information in the central region of Figure A-1 while keeping all other indicators of the interface unchanged. Preview of the additional information was graphically presented for up to 20 kilometers ahead:

speed limits (item 3 in Figure A-2)	track profile (item 6)
signal levels (item 5)	minimum stopping distance (item 11)
station position (item 12)	switch position (not shown)
kilometer posts (item 10)	block boundaries (item 9)

The minimum stopping distance indicated the distance the train will glide before coming to a complete stop under full service braking.

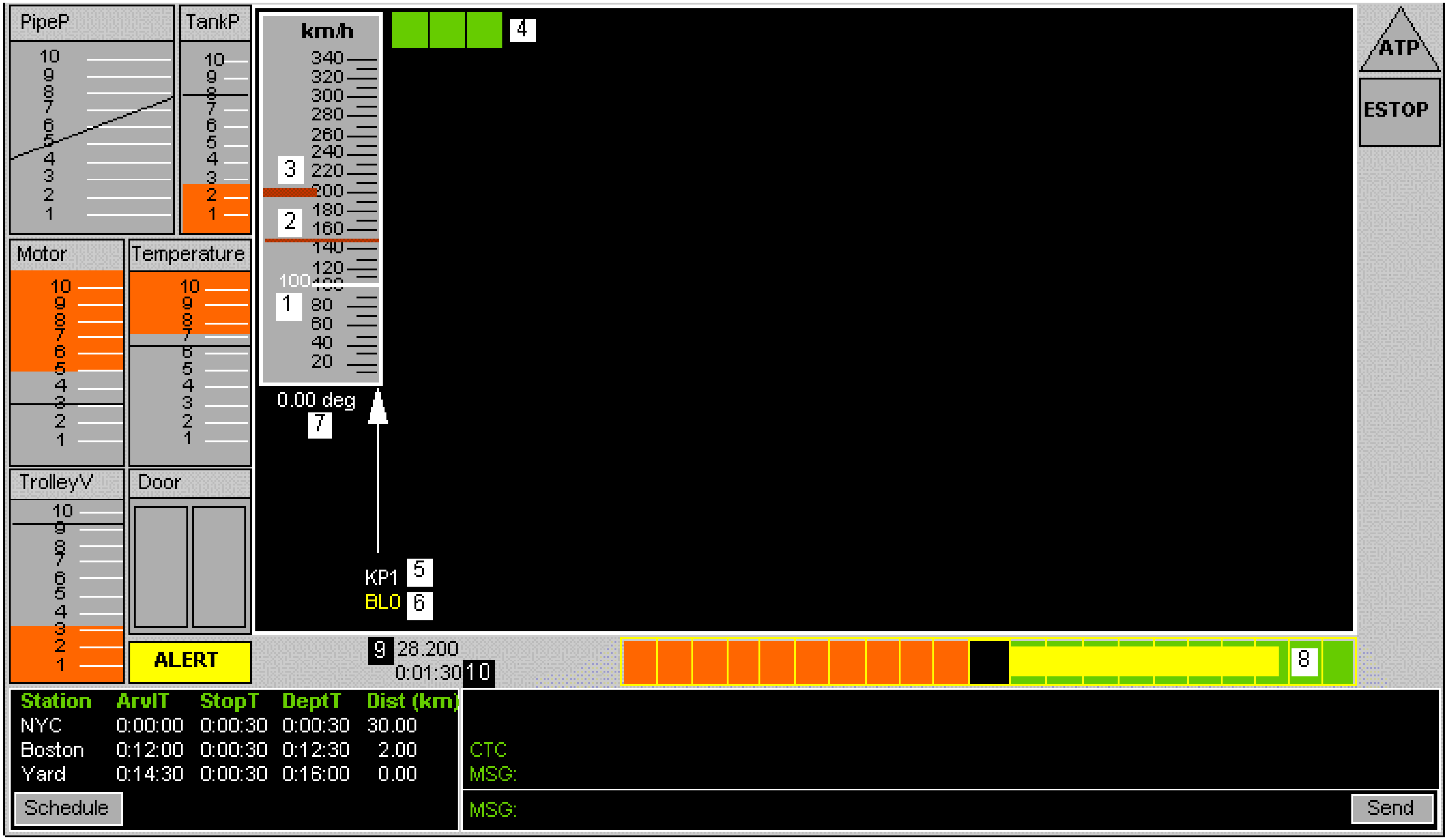


Figure A-1. Primary Cab Indicators and Basic Display. 1: Current speed 2: Civil speed limit of current block 3: Civil speed limit of next block 4: Signal of current block 5: Current kilmeter post 6: Current block number 7: Grade of track at current location 8: Force indicator (traction or braking) 9: Distnace to next station 10: Current time.

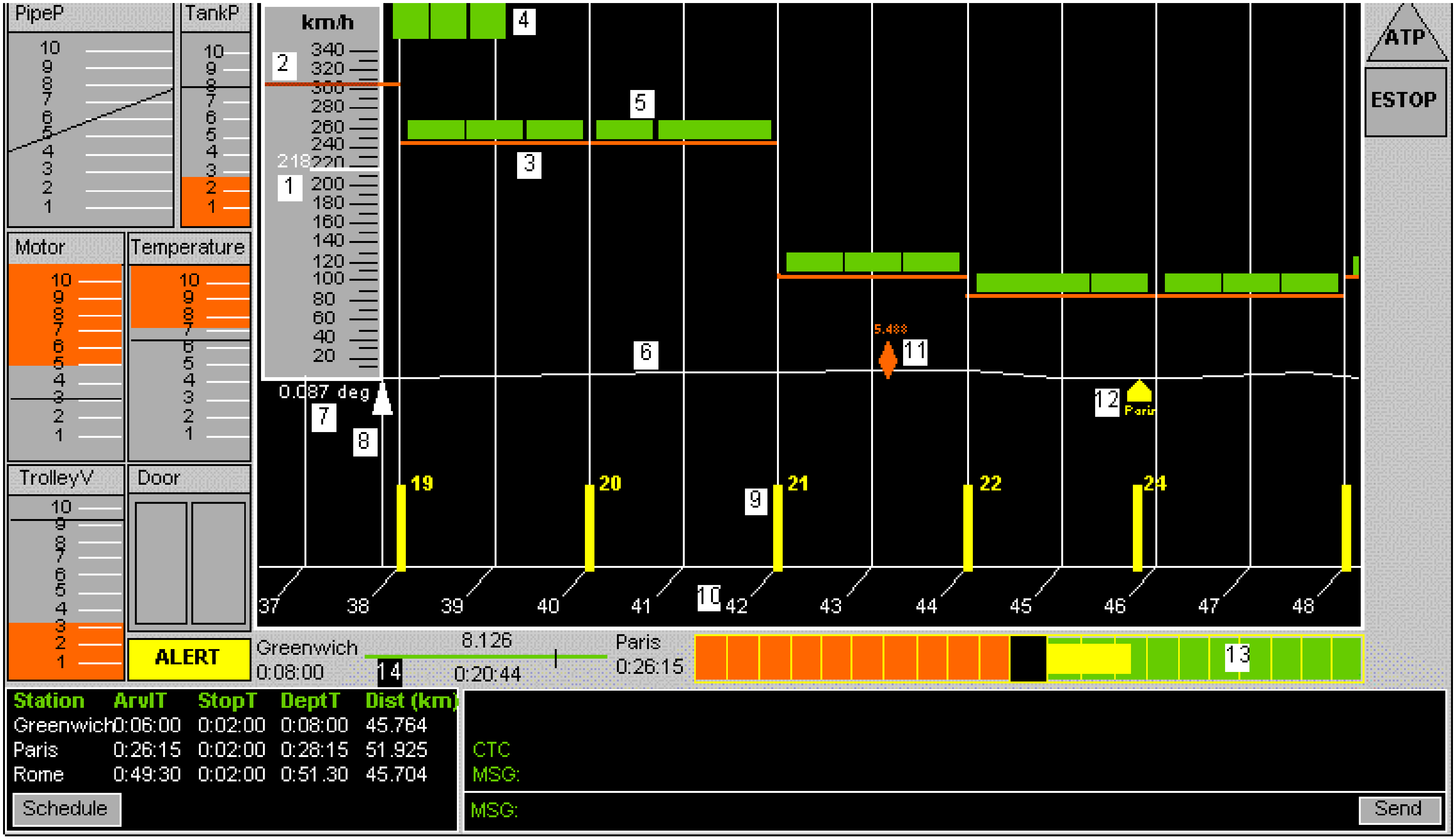


Figure A-2. Primary Cab Indicators and Preview Display. 1: Current speed 2: Civil speed limit of current block 3: Previewed civil speed limits 4: Signal of current block 5: Previewed signals 6: Previewed track elevation profile 7: Grade of current location 8: Location of train 9: Block boundary and number 10: Kilometer post 11: Full-service stopping distance indicator 12: Station 13: Force indicator (traction and braking) 14: Trip-leg overview map.

A.3 EXPERIMENTAL DESIGN

A.3.1 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 the 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 consisting of three trip legs of roughly the same length 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 the current state 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 A-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.

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.

Table A-1. Sequences of Tests and Temporary Freezes.

Sequence #	Run #		
	1	2	3
1	BASIC$^{random, fix}$	PREVIEW^{random}	FAILURE^{fix}
2	BASIC$^{fix, random}$	FAILURE^{fix}	PREVIEW^{random}
3	PREVIEW$^{random, fix}$	BASIC^{random}	FAILURE^{fix}
4	PREVIEW$^{fix, random}$	FAILURE^{fix}	BASIC^{random}
5	FAILURE^{fix}	BASIC$^{random, fix}$	PREVIEW^{random}
6	FAILURE^{fix}	PREVIEW$^{random, fix}$	BASIC^{random}

BASIC = Test with the basic display,
PREVIEW = Test with the preview display,
FAILURE = Test beginning with the preview and with a preview failure in the middle,
( )^{random} = A freeze at a random location during the run ( ),
( )^{fix} = A freeze at the fixed location during the run ( ),
( )$^{random, fix}$ = Two freezes with the random location before the fixed location,
( )$^{fix, random}$ = Two freezes with the fixed location before the random location.

A.3.2 Procedure

Training

The training began with an explanation of the purpose of the study and an overview of the required tasks. A video about rail system operation and tasks of a locomotive engineer, was shown to familiarize the subject with a realistic cab and wayside environment (B&P, 1992). 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 the 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 professional 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 A-1.

A post-test questionnaire on workload 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 on the overall difficulty and their preference on the two displays. The experimental tests required 4 hours per subject to complete.

A.4 RESULTS AND DISCUSSIONS

A.4.1 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 A-3 and A-4, strongly indicate that the preview relieved subjects' workload. In particular, there was a strong trend of reduction in the workload rating with the preview display, compared to that with the basic display (t-test for dependent samples, $p = 0.069$). Ratings of workload were significantly lower before preview failure than after the failure (t-test for dependent samples, $p < 0.01$). Preview also significantly affected the subjects' rating on overall difficulty associated with using the displays ($\overline{X} = 3.5$ with the basic display vs. $\overline{X} = 1.9$

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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.

with the preview display on a scale from 1 to 5) (t-tests, $p < 0.05$). In addition, all subjects preferred the preview display to the basic display for performing the driving task.

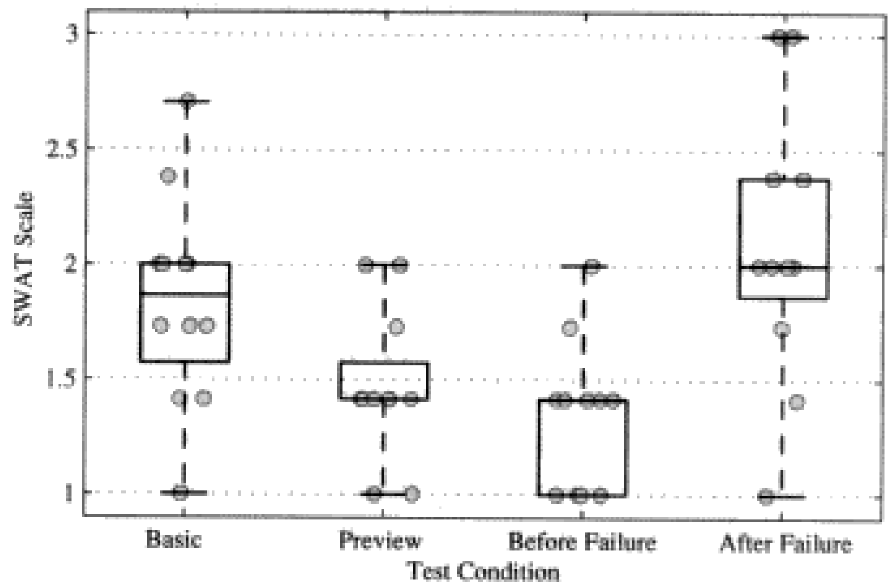

Figure A-3. Measure of Workload in SWAT scale.

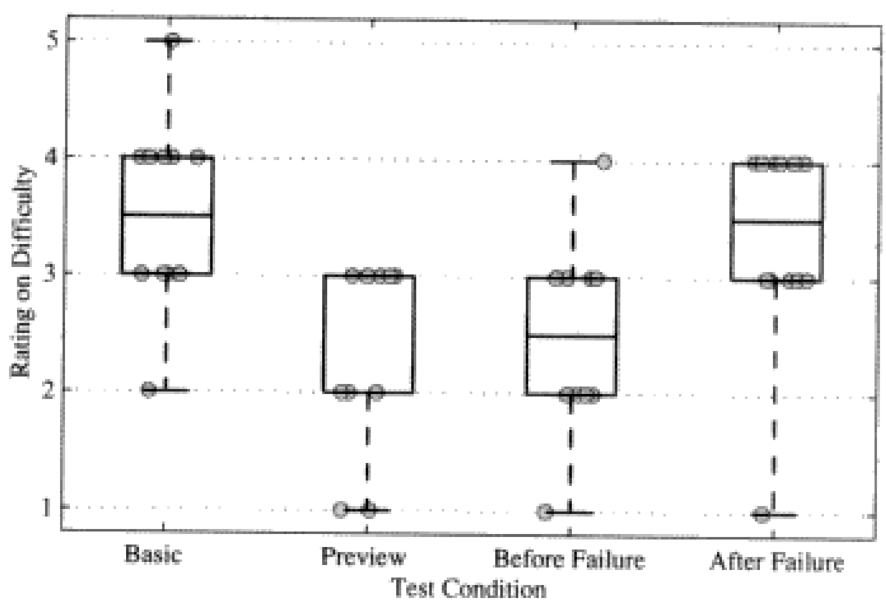

Figure A-4. Overall Difficulty.

A.4.2 Situation Awareness

Each answer to the temporary-freeze queries was compared to actual values, as collected by the simulation computer at the time of the 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 preview display than with the basic display. This evidence indicates that preview improved situation awareness. That subjects lacked training for this experiment, as evidenced in several accounts discussed in section A.4.7, may explain the surprising results from the query method.

A.4.3 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 the 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 aiding is shown to have the potential of increasing safety.

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

A.4.4 Schedule Adherence

Preview aiding 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.

A.4.5 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 stops by inching close to the station after a failure of the first attempt). Among the 36 data points for station stopping (12 subjects, each had three station stops along the test course), 97% stopped within 20 m of the station with the preview display ($\overline{X}$ = 1.6 m) versus 72% with the basic display ($\overline{X}$ = 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.

Note that no out-the-window view was provided in the preliminary experiment. 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.

A.4.6 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 locomotive engineer's throttle manipulation is primarily associated with driving style (assuming they 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.

A.4.7 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, some subjects did not understand some 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 initiated too late to avoid excessive overspeeding, which indicates that subjects under-estimated 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 displays.

APPENDIX B

THE VOLPE CENTER HIGH-SPEED TRAIN SIMULATOR

B.1 MOTIVATION

An important approach to human factors research is experimental investigation. For obvious safety and logistic reasons, however, 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. This study used this simulator to investigate effects of decision aids on locomotive engineer’s 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 the operation of high-speed rail systems.

It should be noted that the simulated system is based on 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.

B.2 FUNCTIONAL REQUIREMENTS

Development of the high-speed train simulator required selection of a signaling system. Although future signaling systems will use "moving blocks" (which can be realized with the global positioning system), a fixed block signaling system was chosen because of its current use 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 locomotive engineer-cab 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 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 locomotive engineer and other onboard systems required more controls. To reduce development cost and time, the computer keyboard and mouse were used for controls not related to manual speed manipulation. No other hardware was involved.

B.3 SIMULATOR MODULES

B.3.1 Overview

As shown schematically in Figure B-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 monitor multiple trains, although only one train simulation is shown under the monitoring of the CTC in Figure B-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 locomotive engineer and the dispatcher is required. Figure B-1 shows the primary simulator configuration used for the experimental investigations conducted for this research and is further described here.

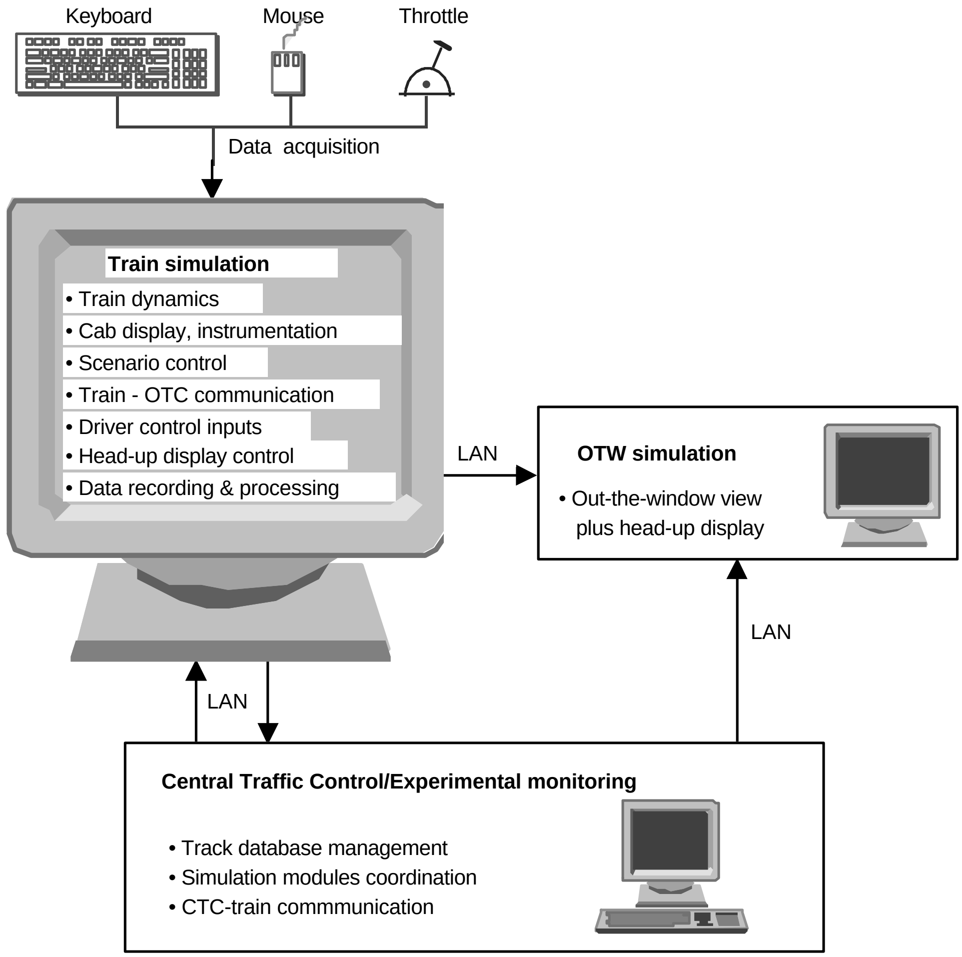

Figure B-1. VNTSC High-Speed Train Simulator. The simulator includes three workstations, a dual-use throttle, computer mouse, and keyboards. The workstations exchange data through a local-area-network (LAN) link. The throttle is interfaced through an analog-digital converter to a serial port of the workstation simulating the cab displays.

B.3.2 Functional Components and Instrumentation

Cab Displays

Instruments and indicators in a basic simulated cab display, shown in Figure B-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 (item 1 in Figure B-2), speed limit of the current block (item 2), and speed limit of the next block (item 3).

To the upper right of the speedometer is the cab signal consisting of three colored lights (item 4). 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 (item 7). 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 (item 6) and KP followed by kilometer post number (item 5). 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) (item 9). Under the distance to the next station is the current time (item 10).

The control interface between the locomotive engineer (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 B-2 (item 8). 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 force level is displayed accordingly. The grid lines on the force indicator are provided as measures of force level at every 10% of the maximum available 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 B-2: the automatic train protection (ATP) system and the emergency stop (ESTOP). (Other functions such as cruise control, automatic control, and programmed station-stopping are available in the simulator, though they were not used in this study.) 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 locomotive engineer (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 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 (ALERT), 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 key) 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 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 locomotive engineer 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. Displays needed for experimental investigation, such as that of a secondary 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 B-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 locomotive engineer. 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 locomotive engineer 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 here, this workstation was used solely for simulation control and for the experimenter to monitor the progress of the subject.

B.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 configured with command-line options. Configuration of other scenarios such as a lead moving train can be set up by manipulating proper command-line options.

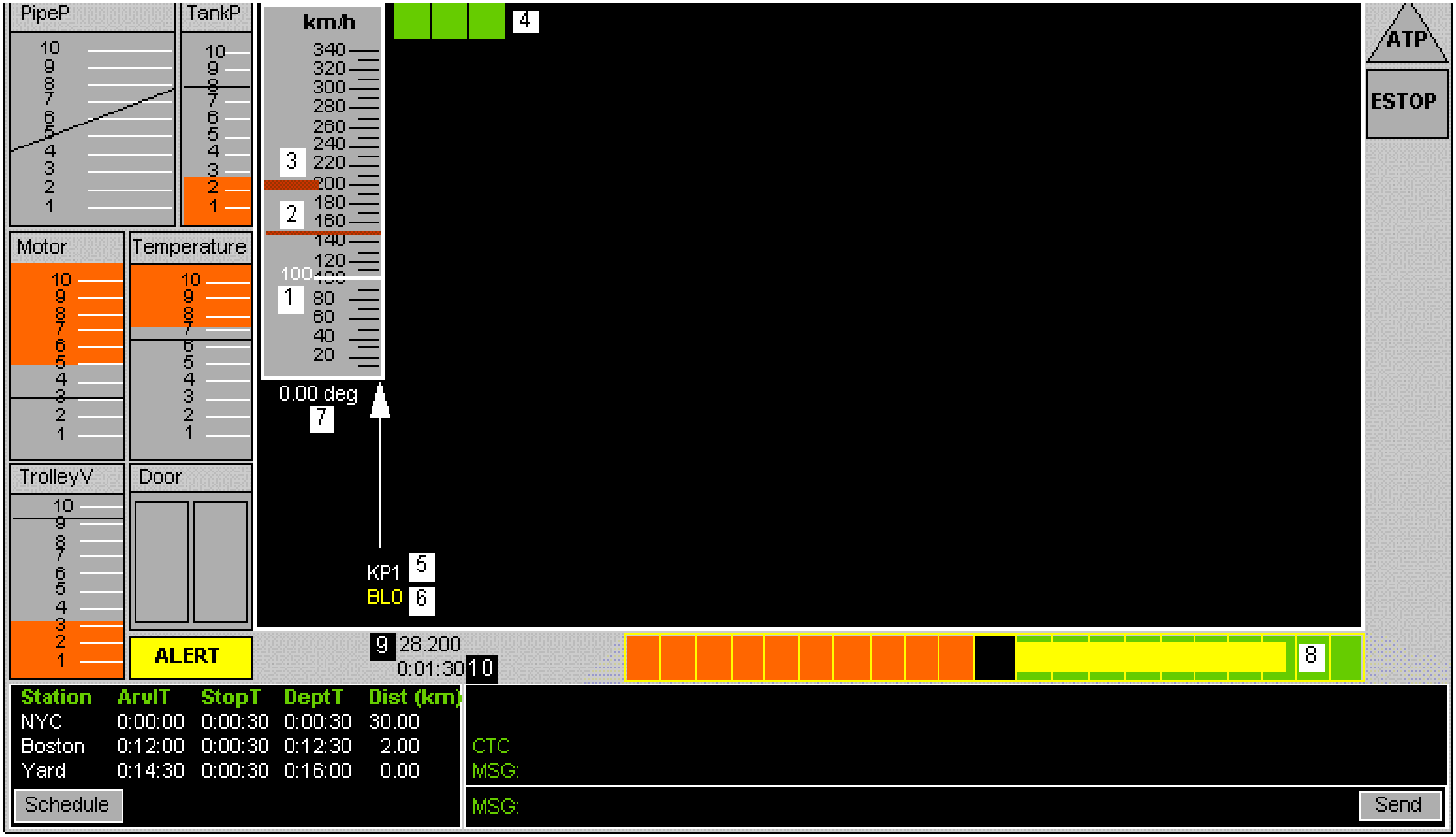

Figure B-2. Primary Cab Instrumentation and Indicators. 1: Current speed 2: Civil speed limit of current block 3: Civil speed limit of next block 4: Signal of current block 5: Current kilmeter post 6: Current block number 7: Grade of track at current location 8: Force indicator (traction or braking) 9: Distnace to next station 10: Current time.

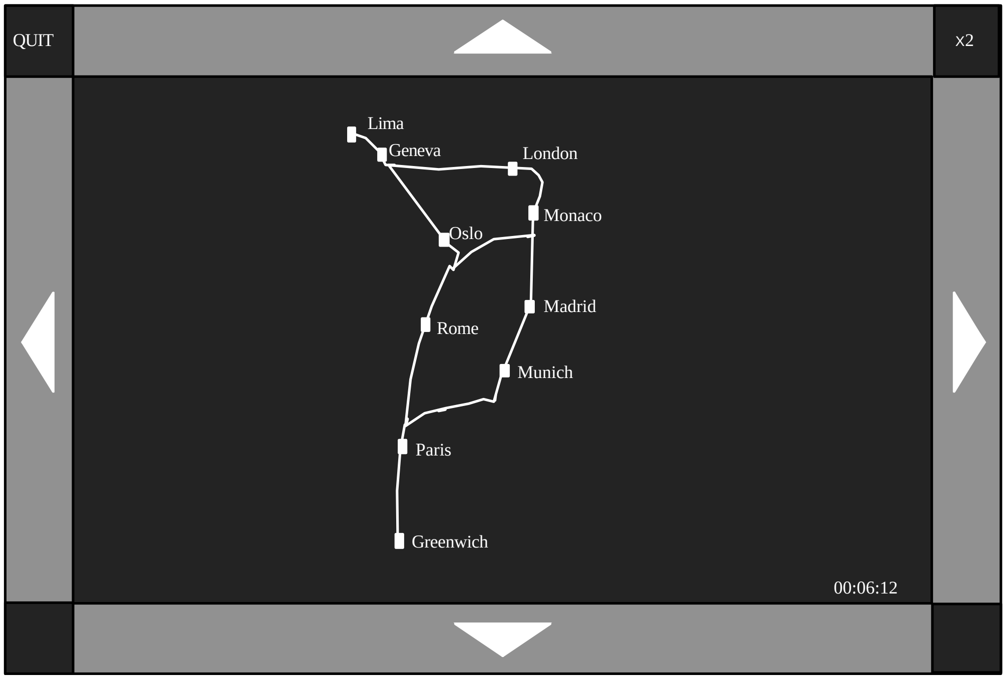

Figure B-3. CTC/Experimental Control Workstation Display. The map shows the rail network under the dispatcher's control or supervision. It can be panned, tilted, and rescaled by mouse clicking on controls at the corners and sides of the map display area. Local zoom in or out can be achieved by clicking 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 C

MODEL OF TRAIN DYNAMICS

C.1 TRAINSET CHARACTERISTICS

Train parameters used for dynamics simulation in this research are those of an Atlantic TGV. Pertinent train characteristics (DOT/FRA, 1991) are listed in Table C-1.

Table C-1. Pertinent Trainset Characteristics

Maximum operating speed	320 km/h (200 mph)
Total train weight (loaded)	418 tonnes (461 tons)
Maximum acceleration	1.534 km/h/s 0.044 g (0.92 mph/s)
Maximum operational deceleration	1.2 km/h/s 0.034 g (0.75 mph/s)
Emergency deceleration	4.32 km/h/s 0.122 g (2.70 mph/s)

C.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 C-1.

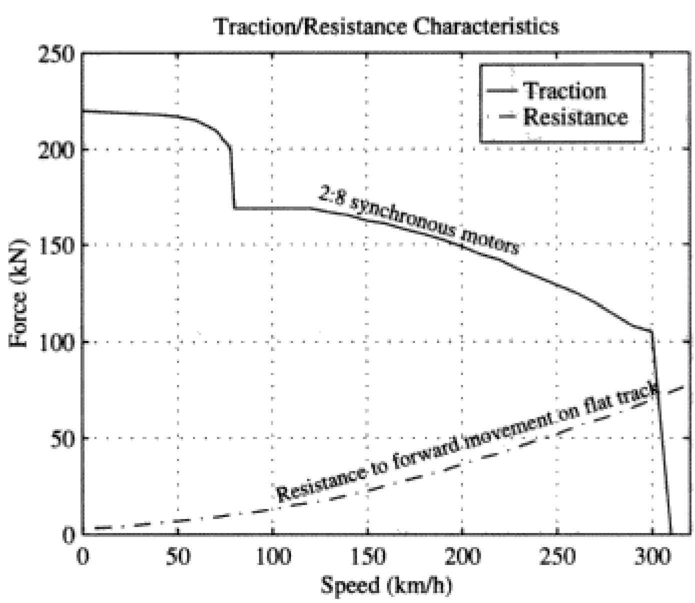

Figure C-1. Traction Characteristics of Atlantic TGV Trainset Under 25 kV - 50 Hz.

C.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* as shown in Figure C-2.

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 aero-dynamic drag), *grade resistance*, and *curvature resistance*. The rolling resistance is all friction and is shown in Figure C-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. The dynamic equations of motion are:

$$\frac{dx}{dt} = v(t)$$

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

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

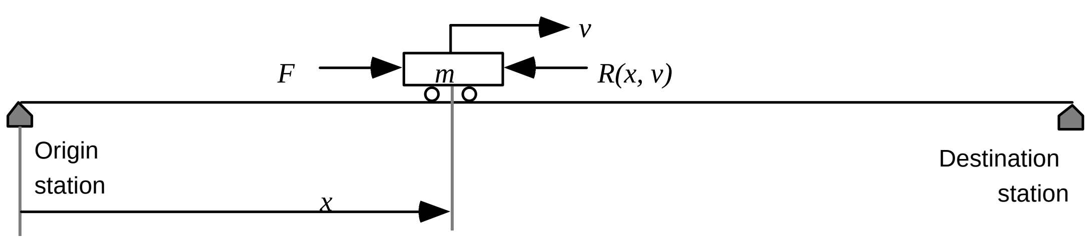

Figure C-2. Modeling the Motion of a High-Speed Train.

APPENDIX D

RAIL SIGNALS

This appendix 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 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 D-1 illustrates the 6-block 7-aspect block signaling system. The seven 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 D-1.

Table D-1. Signal Aspects and Signal Speeds

Signal Aspect*	Signal Speed (km/h)	Definition of the Aspect
GGG	300	Proceed
GYG	300	Proceed approaching next signal at 270 km/h
YGY	270	Proceed approaching next signal at 220 km/h
YYY	220	Proceed approaching next signal at 160 km/h
YRY	160	Proceed approaching next signal at 80 km/h
RYR	80	Proceed preparing to stop
RRR	0	Stop, do not enter.

* *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 D-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 mechanism that provides such a functionality is an automatic interlocking system.

The meaning of a signal aspect to the locomotive engineer 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 locomotive engineer, 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 locomotive engineer 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 locomotive engineer 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.)

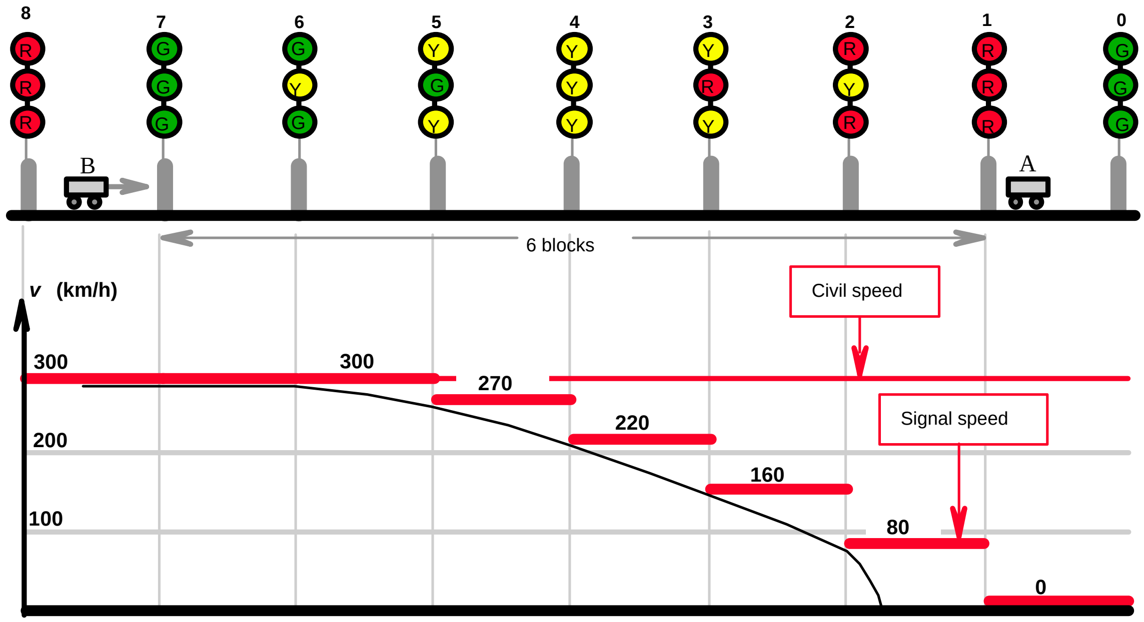

Figure D-1. The 6-Block 7-Aspect Block Signal System. *Top*: Signal aspects displayed to protect this piece of road (of identical 2-km blocks). *Bottom*: Illustration of corresponding signal speeds following an occupied block. Assume that train A has stopped in block 1 (the number above the signal lights 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 locomotive engineer 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.

APPENDIX E

OBTAINING THE MINIMUM-ENERGY SPEED TRAJECTORY

E.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 *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 and propulsive capabilities, schedule, speed limits along the track, and passenger ride quality.

Assuming a non-regenerative braking system[†], 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 and 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 technique of the 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. The equality schedule constraint is introduced into the cost 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 such 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 E-1. The length of the segments, denoted by *Dx*, should be so small that each track segment can be characterized with constant grade and curvature. For a high-speed

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† Calculation of energy consumption depends on the assumption on energy supply and train braking systems.

passenger train, the length of the train is short enough (about 70 meters) for the train to be modeled as a solid mass *m* since the internal forces between the cars can be neglected. Hence, the train's motion in one segment can be modeled with a constant acceleration.

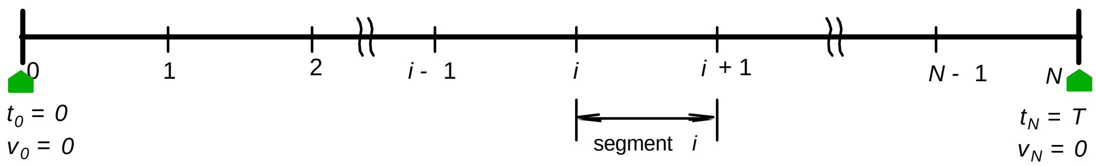


Figure E-1. The *N* Segments of the Track From the Origin to the Destination.

For each segment *i*, (i = 0, ..., N-1), let v_i be the train's speed at location x_i, let Dt_i, $\Delta t_i = t_{i+1} - t_i$, 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_t 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

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

where the two weights should be such that the total time over the trip along the optimal speed trajectory satisfies the following equality:

$$\sum_{i=0}^{N-1} \Delta t_i = T \ .$$

The minimization is taken over the following sets of constraints:

(1) $-F^{max\ braking} \le F_i \le F^{max\ propulsion}(v_i^{avg})$,

where v_i^{avg}, $v_i^{avg} = \frac{v_i + v_{i+1}}{2}$, is the average speed in segment *i*;

(2) $v_i \le \overline{V}_i$, where $\overline{V}_i$ is the speed limit at location x_i.

(3) $\frac{a_{i+1} - a_i}{\Delta t_i} \le jerk\_tolerance$,

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

E.2 SOLUTION BY DYNAMIC PROGRAMMING TECHNIQUE

The above optimal-trajectory problem was solved using a dynamic programming technique iteratively. The iteration was to search for the desired ratio of the two weights, w_e and w_t. 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_t such that $\sum_{i=0}^{N-1} \Delta t_i = T$ holds exactly for the minimum-cost trip.

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

For a given w_t, the following optimization was performed. Let the cost over segment *i* be c_i,

$$c_i \equiv w_e |F_i| \Delta x + w_t \Delta t_i ,$$

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* states that (Bellman and Dreyfus, 1962)

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

This recursive equation was 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, $0 \le v_k \le \overline{V}_k$, referred to the speed at location x_k. The continuous range of state v_k was discretized into I_k+1 discrete values, $0, \ \Delta v, \ 2\Delta v, \ \ldots, \ I_k \Delta v$, where *Dv* was a parameter chosen for the dynamic programming procedure and $I_k = \frac{\overline{V}_k}{\Delta v}$. Therefore, the states at stage *k* could be written as $v_k = i \bullet \Delta v, \ i = 0, \ \ldots, \ I_k$.
2. Another concept was the *possible state*. Since there were constraints on control force, it might not be possible to get to v_N at stage *N* from every state v_{N-1} at stage *N*-1. In this case, $J_{N-1}(v_{N-1})$ was only defined for those v_{N-1} from which it was possible to get to v_N—the final known state of the trip. Similarly, $J_{N-2}(v_{N-2})$ was only defined for those v_{N-2} from which it was possible to get to at least one possible state at stage *N*-1, and so on. Therefore, a possible state at stage *k* was a value of v_k from which it was possible to get to at least one possible state at stage *k*+1. The known state of the last stage, v_N, was a possible state.
3. From each state, at a given stage *k*, the cost to get to stage *k*+1 was a function of the two states.

The backward dynamic programming (Figures E-2 and E-3) started with stage *k* = *N*-1 since the possible state v_N at stage *N* was given or fixed. All paths from each possible state at stage *N*-1 to the final state v_N were least-cost since there was 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 were then stored for use in the next stage (Table E-1).

At stage *k*, the least-cost path from each state v_k to the final state v_N was 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 was simply to add the cost from v_k to the possible state v_{k+1} at stage *k*+1 and the minimum cost from v_{k+1} to the final state v_N which had been calculated in the previous stage and recorded (in the form of Table E-1). In the mean time, a new table that contained the minimum cost and the acceleration for the current stage *k* was constructed while searching for the least-cost path from each state v_k, $v_k = i \bullet \Delta v, \ i = 0, \ \ldots, \ I_k$ to the final state v_N.

Table E-1. Values Stored for Stage *K*

v_k	$a_k(v_k)$	$J_k(v_k)$
0	—	—
Dv	—	—
$2Dv$	—	—
.	.	.
.	.	.
.	.	.
I_kDv	—	—

Having completed the least costs and best paths for stage N-2, the table for stage N-1 could be discarded since in determining costs at stage N-3, only the costs from the previous stage, N-2, to the final state were 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 could be similarly found, and so on with the remaining stages. When the least-cost path for the last stage $k = 0$ was obtained, the optimal solution could be retrieved from the best-path information stored during the backward programming process.

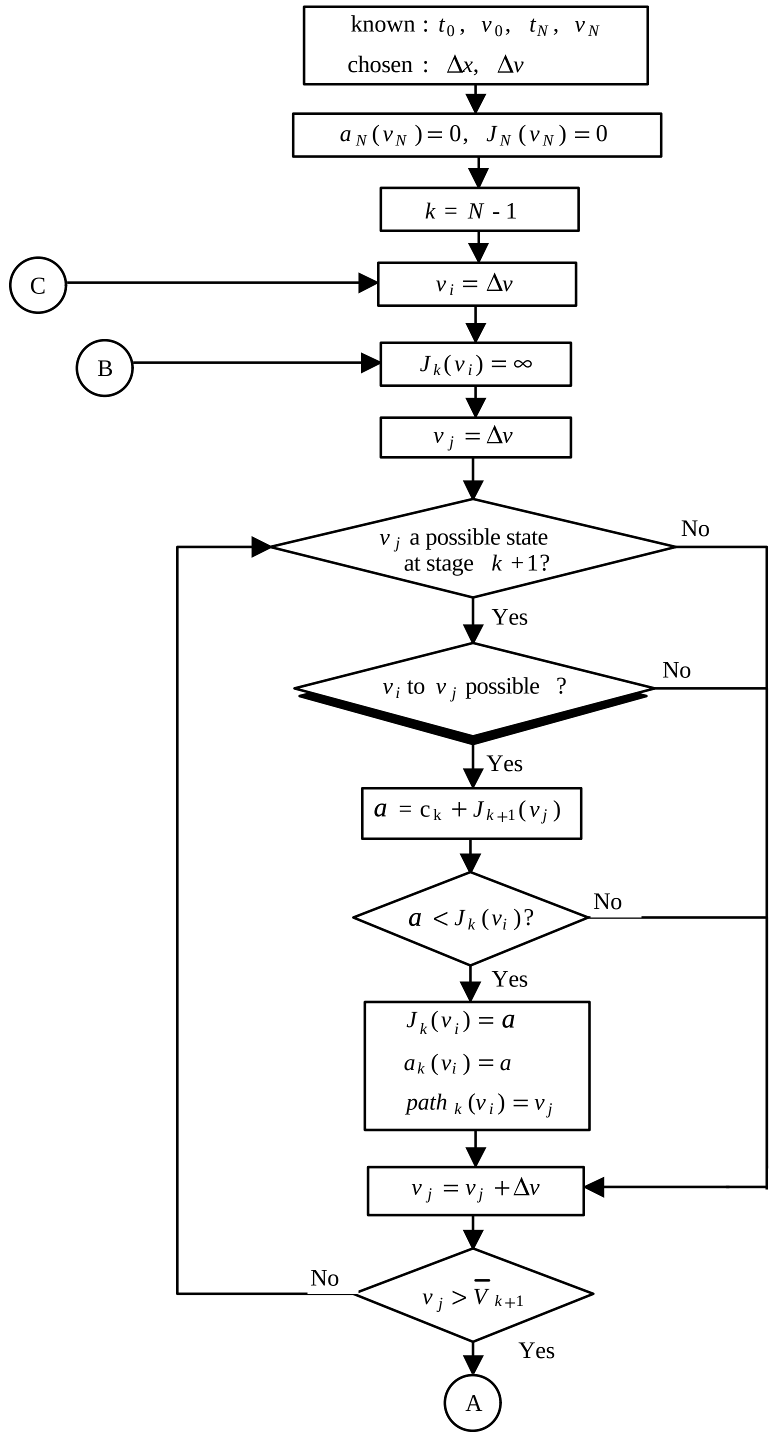


Figure E-2. Flow Chart of Dynamic Programming For Solving for the Optimal Speed Profile (Cont. next page)**.** The heavy-framed block is decomposed in Figure E-3. The "∞" represents a large positive number.

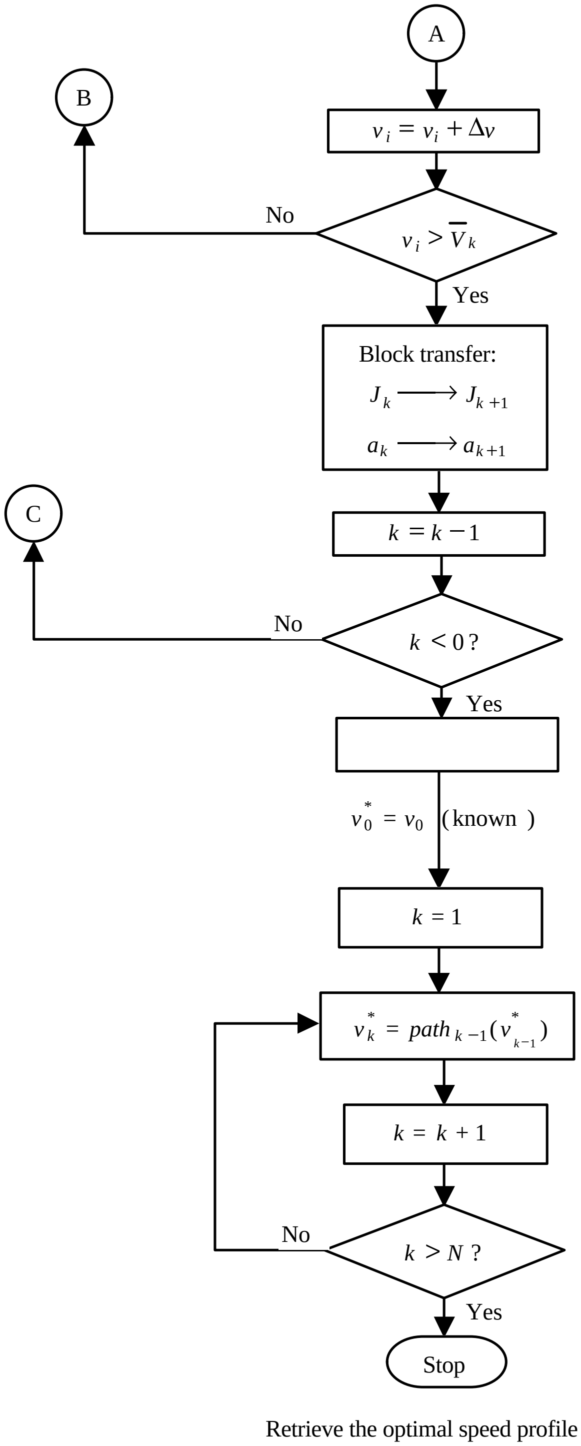


Figure E-2 (Cont'd). Flow Chart of Dynamic Programming For Solving the Optimal Speed Profile.

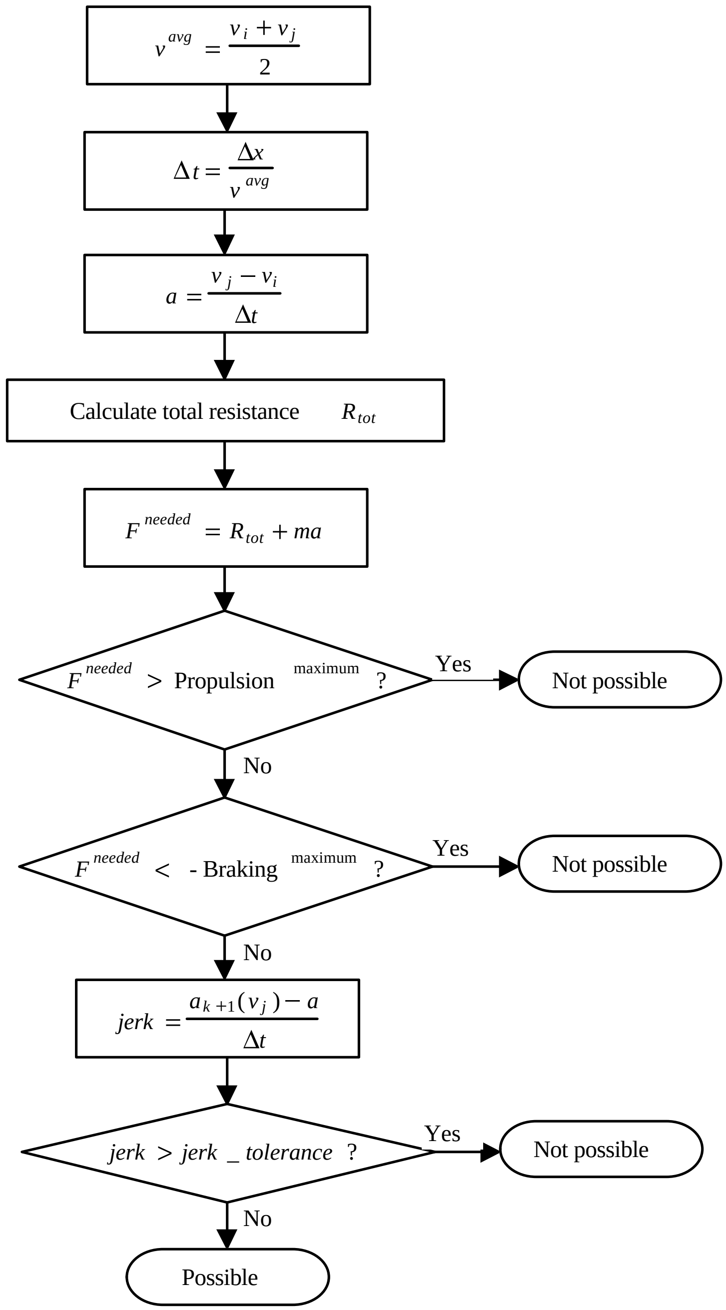


Figure E-3. Flow Chart of Testing if it is Possible to Reach v_j at stage k+1 From vi at Stage k.

APPENDIX F

GUIDE TO OPTIMAL THROTTLE MANIPULATION

En route			
Action	**Location (KP*)/when**	**Speed (km/h)**	**Landmark**
Accelerate (100% gradual reduction to 94% propulsion)	0	0	NYC station
Cruise (34~38% propulsion)	9	240	Christmas trees
Accelerate (~90% propulsion)	14	240	Twin blue towers
Coast (throttle neutral)	17	~259	Red overhead bridge
Coast/Small braking (~2%)	19		Red ancient gate
Large braking (90~100%)	23.2	222	Twin blue tilted towers
Cruise (~4% propulsion)	28	70	Red China gate
	(~800m to station)		Head-up display shows up
Approach Station With The Basic Display			
Approach station	(~600m to station)	70	Out-the-window view—4th set of tunnel lights crosses head-up display
Check and adjust		~60	3rd set of lights...
Check and adjust		~50	2nd set of lights...
Check and adjust		~40	Station wall...
Check and adjust		~18	Top of station signal sign...
Reduce braking to ~25% to avoid jerky stop	Just before train stops	2~1	

* KP—kilometer post

APPENDIX G

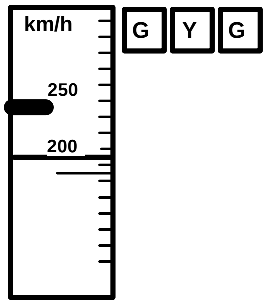
IN-CLASS EXCERCISES

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

The figures on 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.).

Example 1



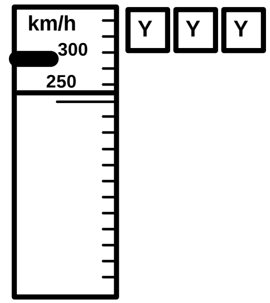
Just entered Block 1

Current block _________ (km/h)

Next block _________ (km/h)

ATP _______________

Example 2



Just entered Block 1

Current block _________ (km/h)

Next block _________ (km/h)

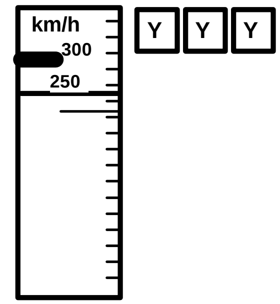
4 km ahead _________ (km/h)

6 km ahead _________ (km/h)

10 km ahead _________ (km/h)

ATP _______________

Example 3



Just entered Block 6

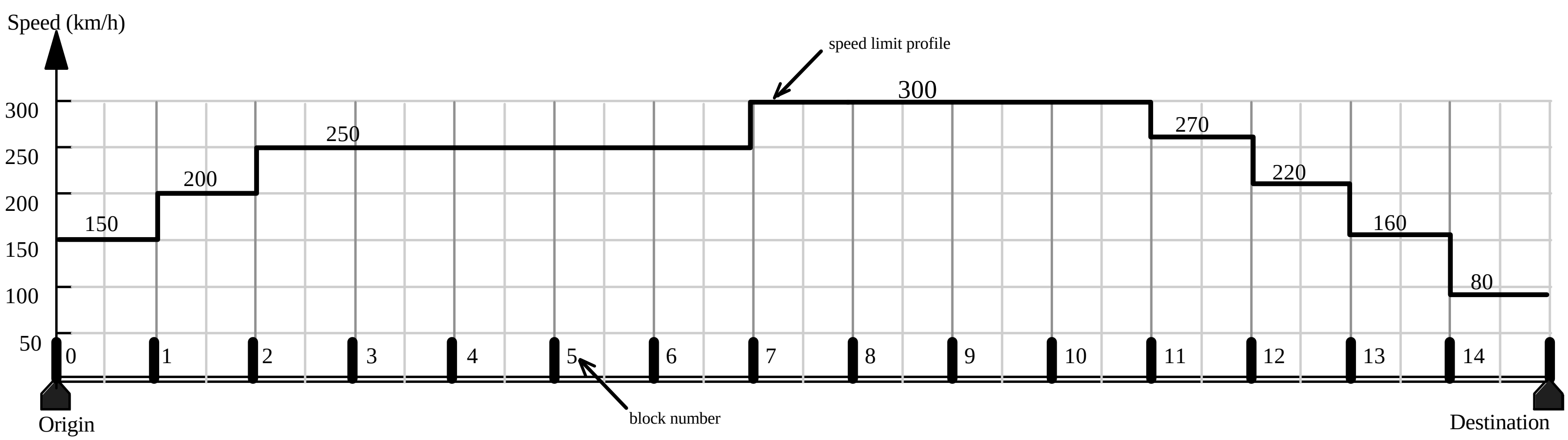
Current block _________ (km/h)

Next block _________ (km/h)

4 km ahead _________ (km/h)

6 km ahead _________ (km/h)

ATP _______________



APPENDIX H

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 at 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:

Block #	0	1	2~6	7~10	11	12	13	14
Speed limit (km/h)	150	200	250	300	270	220	160	80

(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)

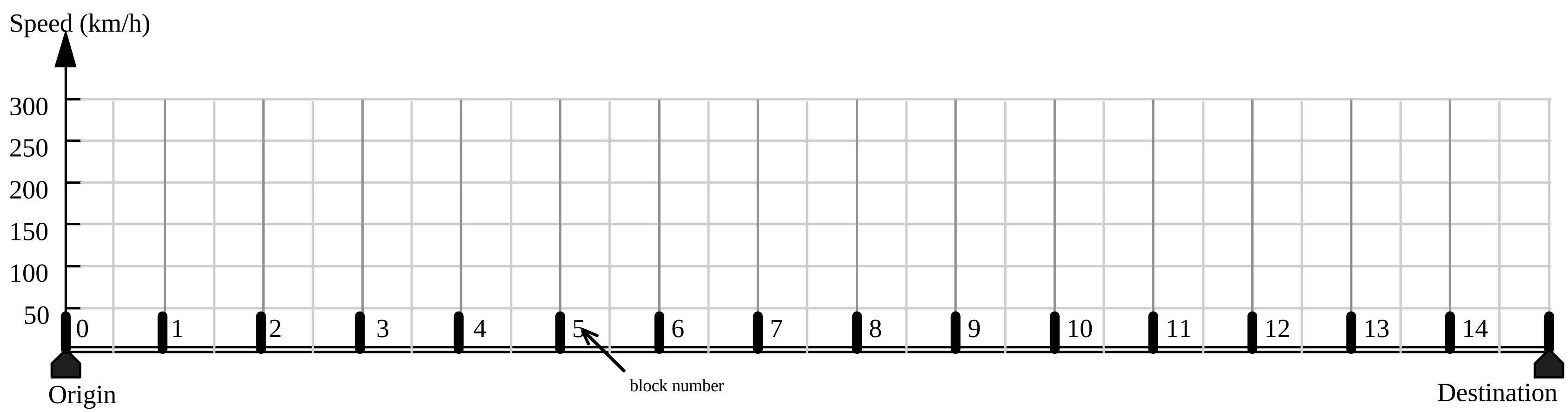


Figure 1

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?**

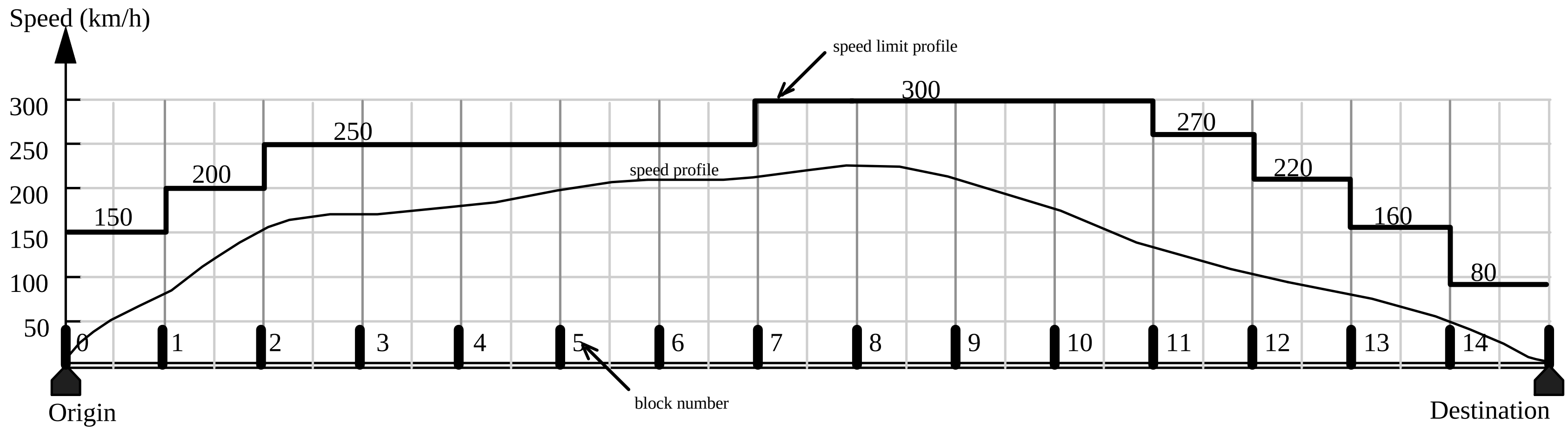


Figure 2.a

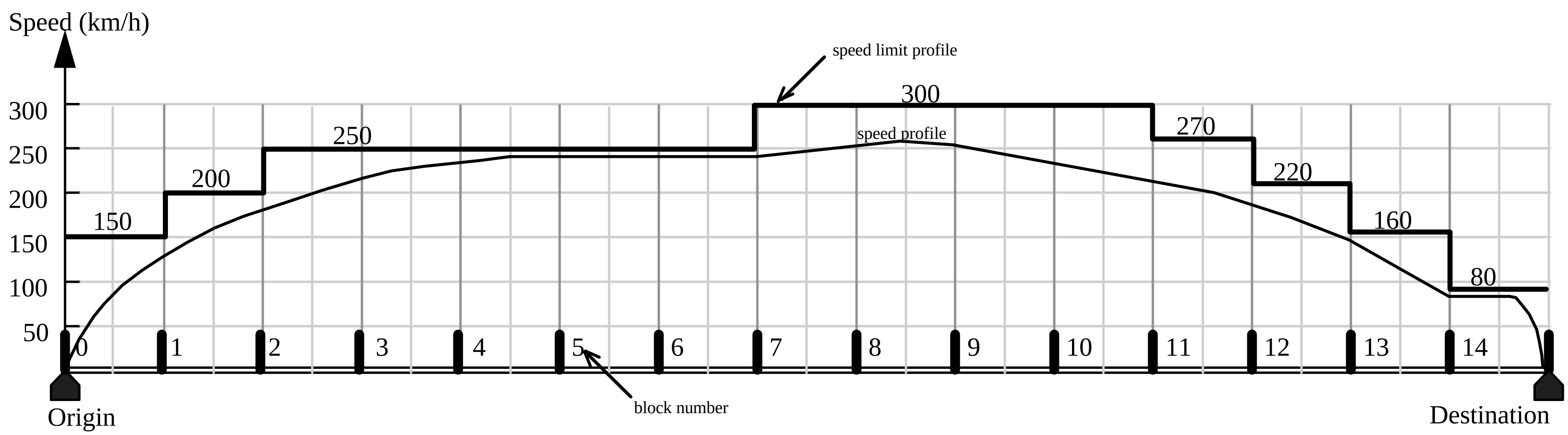


Figure 2.b

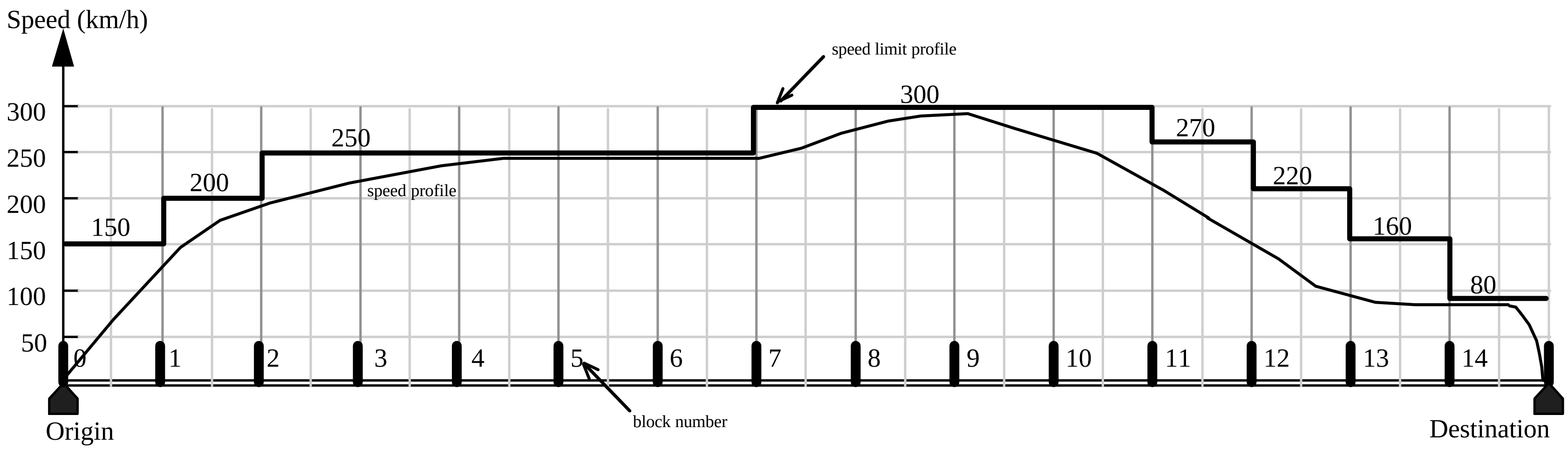


Figure 2.c

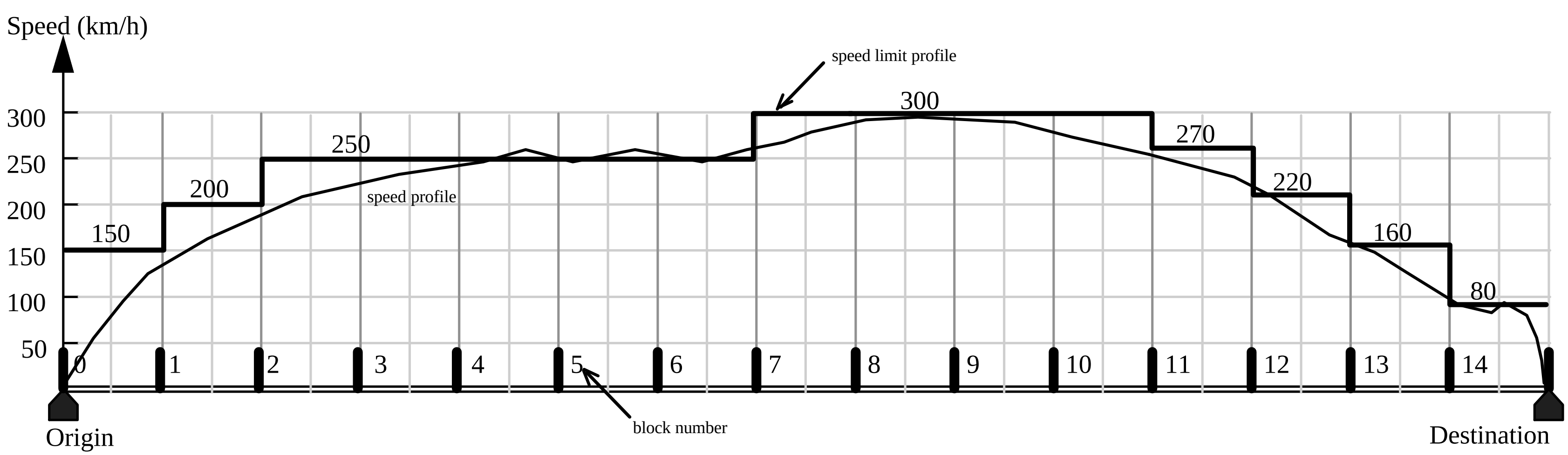


Figure 2.d

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.

(c) 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).

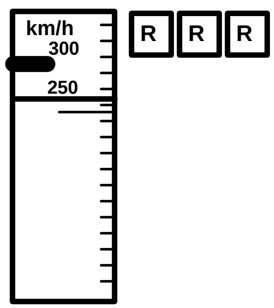
(d) If emergency stop is activated out of careless speed control.

(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).

5. Figures 5.a - 5.c show three possible speed limits-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.d. 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).

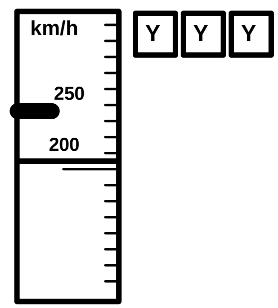
Please fill in the effective speed limits asked under each figure. In addition, explain what action the ATP (Automatic Train Protection) system would take if the it functions properly (does nothing, beeps and flashes yellow, activates the emergency stop and turns red, etc.).

Figure 5.aFigure 5.b Figure 5.c



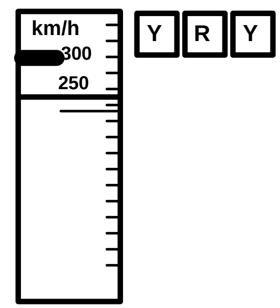
Just entered Block 6

Current block __________ (km/h)
Next block __________ (km/h)
ATP __________________



Just entered Block 1

Current block __________ (km/h)
Next block __________ (km/h)
4 km ahead __________ (km/h)
6 km ahead __________ (km/h)
ATP __________________



Just entered Block 6

Current block __________ (km/h)
Next block __________ (km/h)
ATP __________________

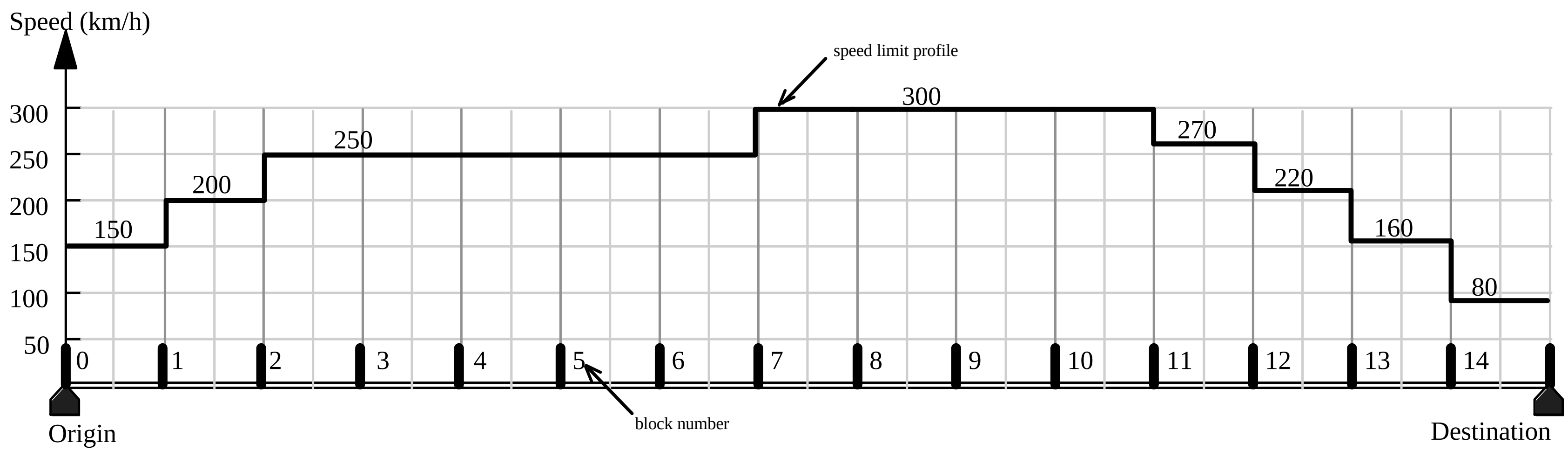


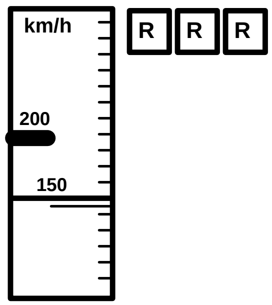
Figure 5.d

6. Please answer the following questions. A rough estimate is enough.

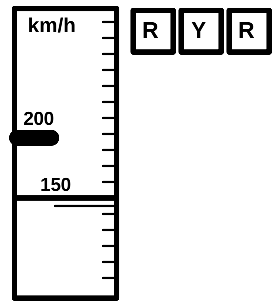
(a) **What is the stopping distances when the speed of the train is**

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

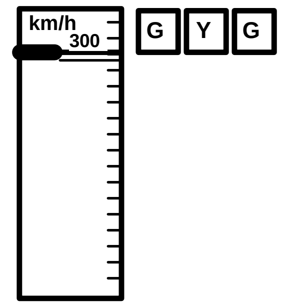
6. (b) Assume that the ATP (automatic train protection) system has failed and you encounter the following situations. **What should be your responses?** Choose one answer.



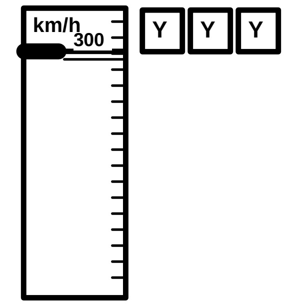
(a) Full-service braking only.
(b) Full-service braking, then, emergency stop when speed is lower.
(c) Emergency stop immediately.



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

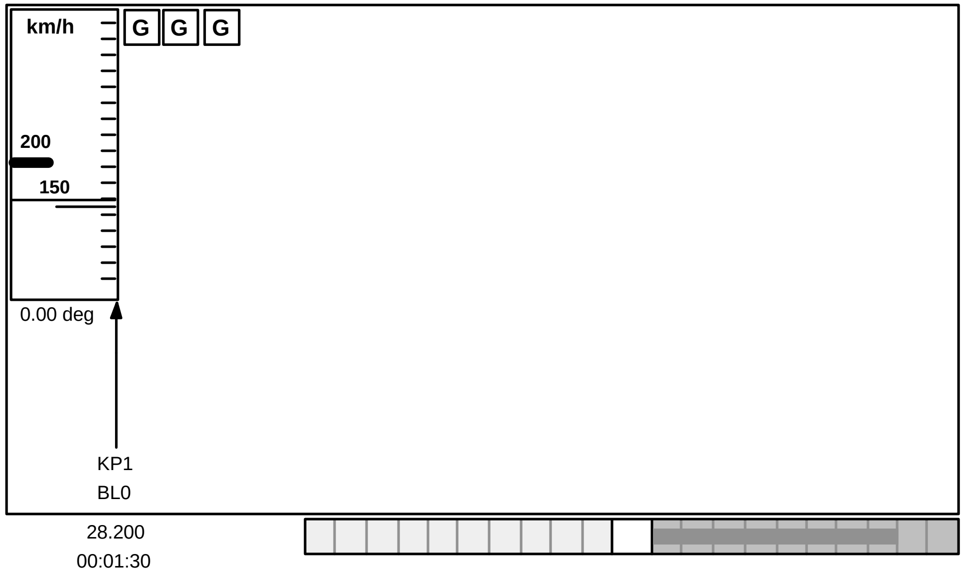


(a) Full-service braking only.
(b) Full-service braking, then, emergency stop when speed is lower.
(c) Emergency stop immediately.



(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)

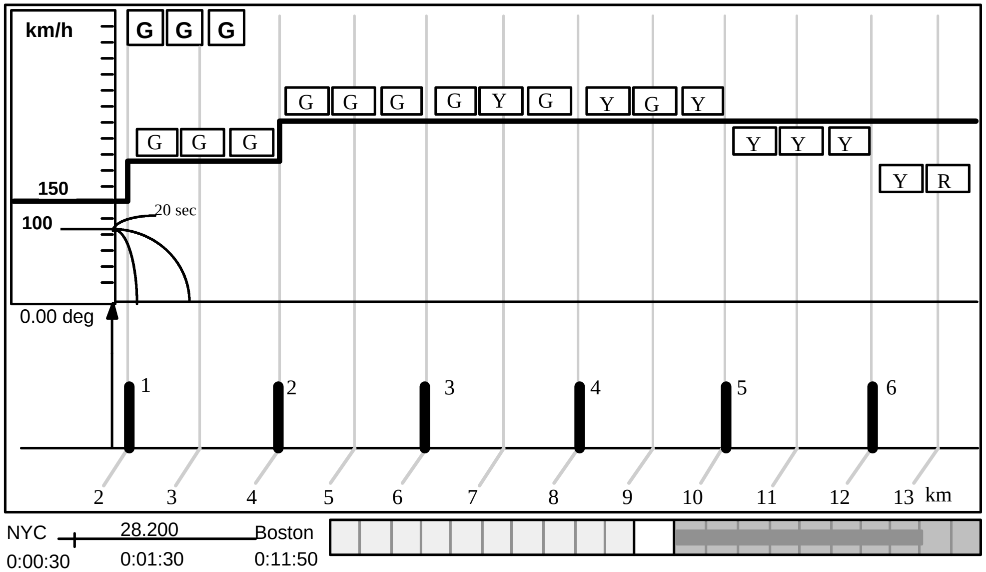
(6) What's the current time? ___________

(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? ____________

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 the train's speed be 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) Approximately, how long is the emergency stopping distance at the current speed? ___________

(6) The effective speed limit at block 6 at this moment is ___________

(7) The destination of the trip is ___________

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

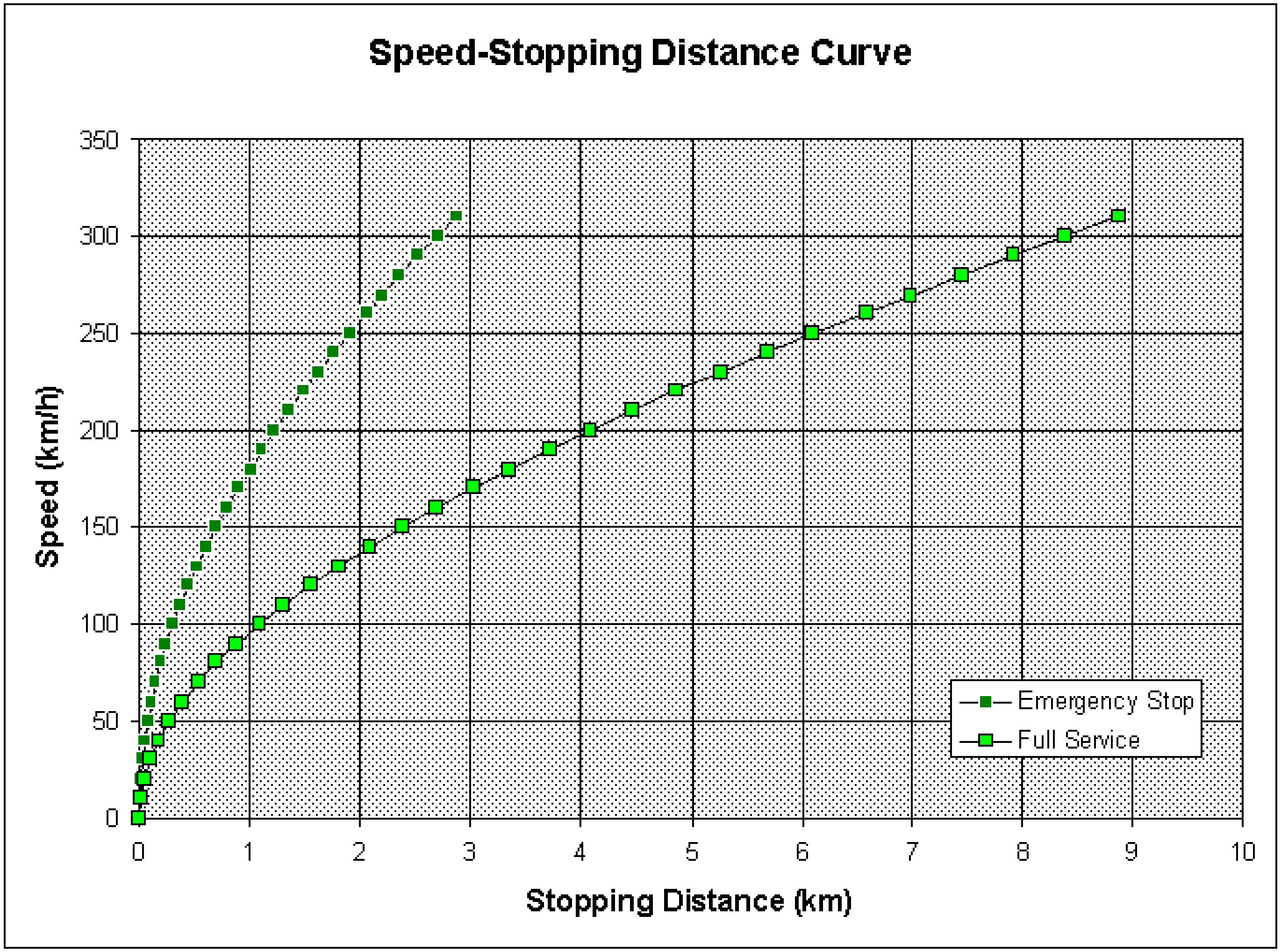
APPENDIX I

TABLE OF STOPPING DISTANCES

Speed (km/h)	***Stopping distance —full-service (km)***	***Stopping distance — emergency (km)***
300	8.390	2.704
240	5.684	1.765
80	0.706	0.201
70	0.534	0.153
60	0.400	0.114
30	0.101	0.028
20	0.045	0.012
10	0.011	0.001

APPENDIX J

SPEED-STOPPING DISTANCE CURVE



APPENDIX K

INCENTIVE SYSTEM

Bonus Comparison Table

(For Routine Speed Control)

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

* 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: Ten percent 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 K-1.

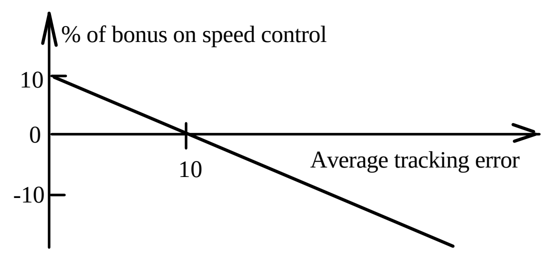


Figure K-1. Additional Bonus On the Secondary Task. The additional bonus was awarded as a percentage of the bonus earned on the routine speed control.

Bonus System

(For Runs with Emergency Scenarios)

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 K-1):

- When emergency braking was activated to avoid a red-light overrun, between 10 and 20 points were awarded depending on the activation-speed. The lower the activation-speed, the more points were awarded. The activation-speed can be reflected with the distance between the train's stop point and the red lights. The shorter the distance the train is stopped before the red lights, the lower the activation-speed has been.
- 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 K-1. Incentive System For Runs With Signal Event.

Outcome	Bonus Points
Safe Stop With Full-Service Braking	25
Safe Stop With Emergency Braking	$10 + 10\left(1 - \frac{\text{distance to red lights at stop}}{\text{maximum possible distance to red lights at stop}}\right)$
Red-Light Overrun	$-10 \times \frac{\text{speed at red-light overrun (km/h)}}{50}$

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

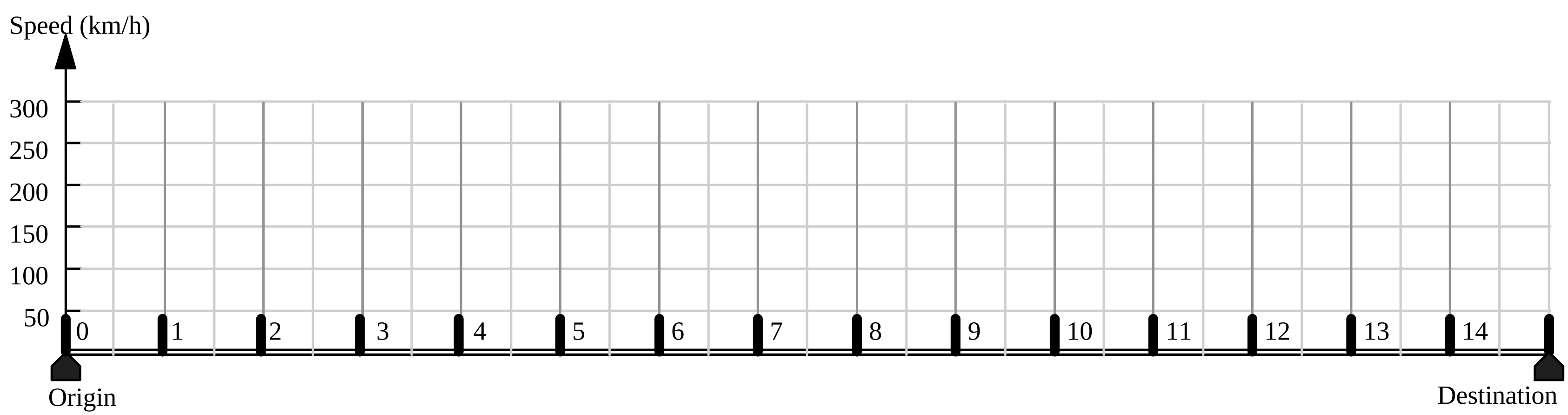


Figure 1

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.

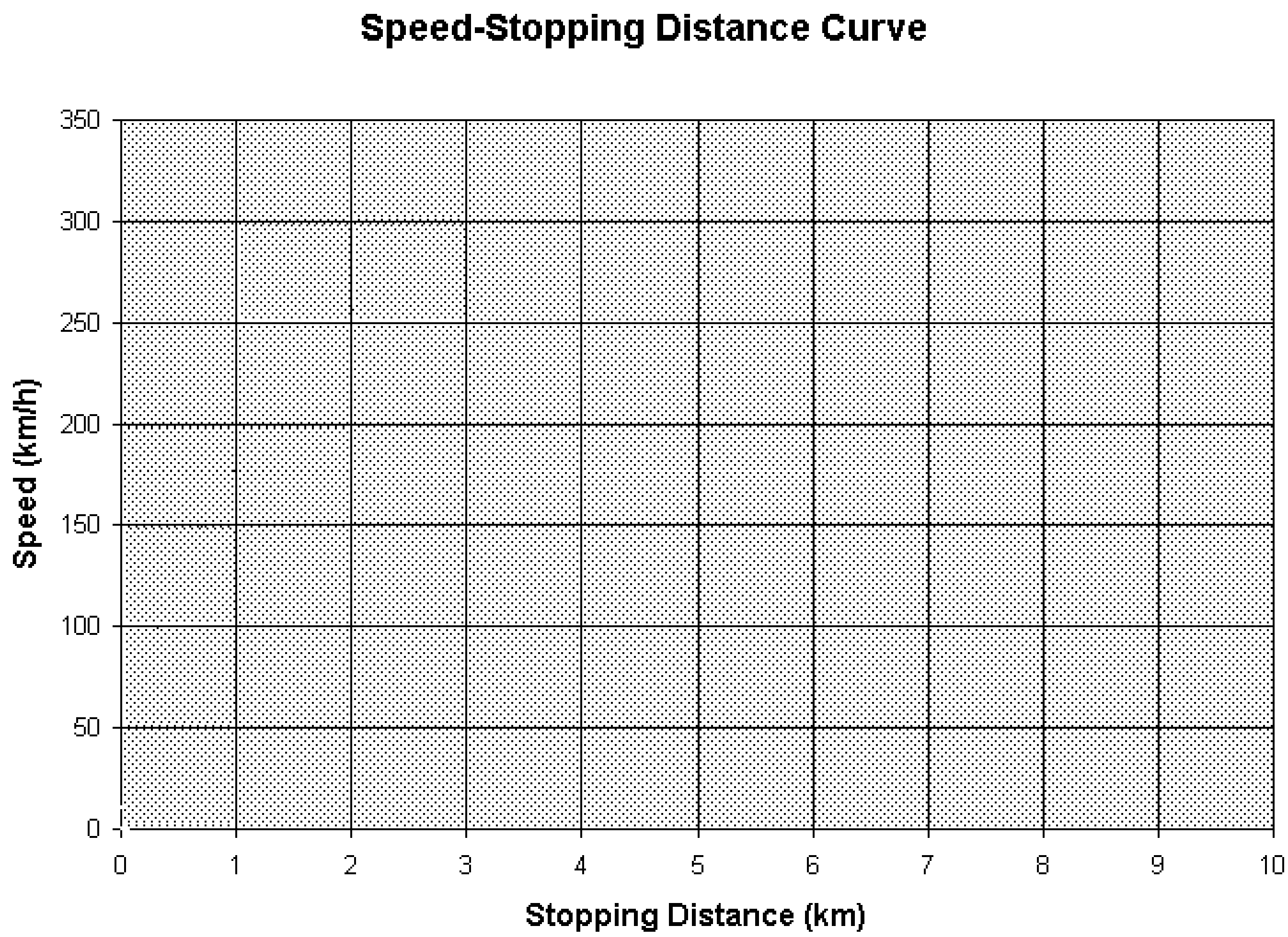


Figure 2

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.

_____ _____ _____ : ______ km/h

_____ _____ _____ : ______ km/h

_____ _____ _____ : ______ km/h

_____ _____ _____ : ______ km/h

_____ _____ _____ : ______ km/h

_____ _____ _____ : ______ km/h

_____ _____ _____ : ______ km/h

(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.

APPENDIX M

WORKLOAD ASSESSMENT—IMMEDIATE AND ABSOLUTE

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.

1	2	3	4	5	6	7
↑						↑
plenty of spare time, no overlap of activities.						*almost no spare time, very frequent overlap of activities.*

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.

1	2	3	4	5	6	7
↑						↑
very little concentration required, activities are almost automatic.						*high concentration required, highly complex activities.*

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.

1	2	3	4	5	6	7
↑						↑
low stress, very little confusion or frustration.						*high stress, high determination and self-control required.*

APPENDIX N

WORKLOAD ASSESSMENT—RETROSPECTIVE AND RELATIVE

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 a higher workload than that for all test runs with the *basic* display. Correspondingly, a rating value smaller than 100 means a 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?

APPENDIX O

IMPLEMENTATION OF LOCOMOTIVE ENGINEER MODEL

O.1 STRUCTURE OF THE MODEL

The structure of the rule-based locomotive engineer model is described with hierarchical functional block diagrams in this appendix. 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 O-1 shows the top level block diagram of the locomotive engineer model. The block diagram of perception, together with other block diagrams describing rules implemented in the model, are shown in Figures O-3 through O-12.

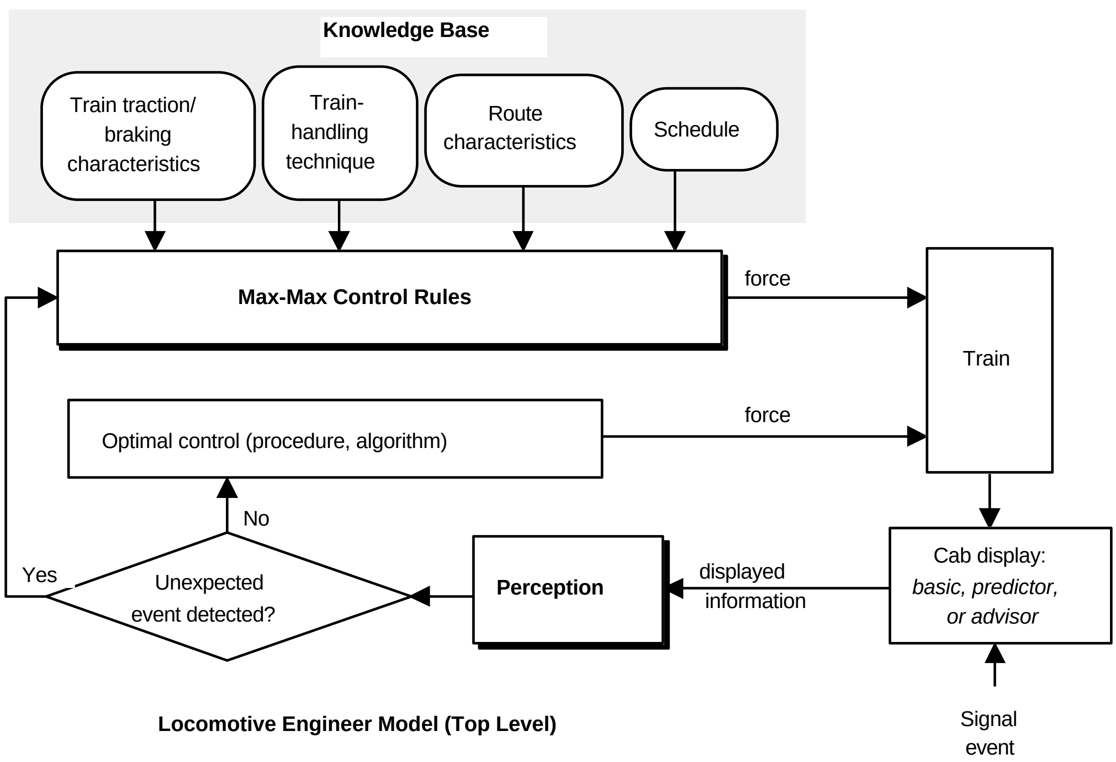


Figure O-1. Locomotive Engineer Model (top level).

O.2 HIERARCHICAL BLOCK DIAGRAMS

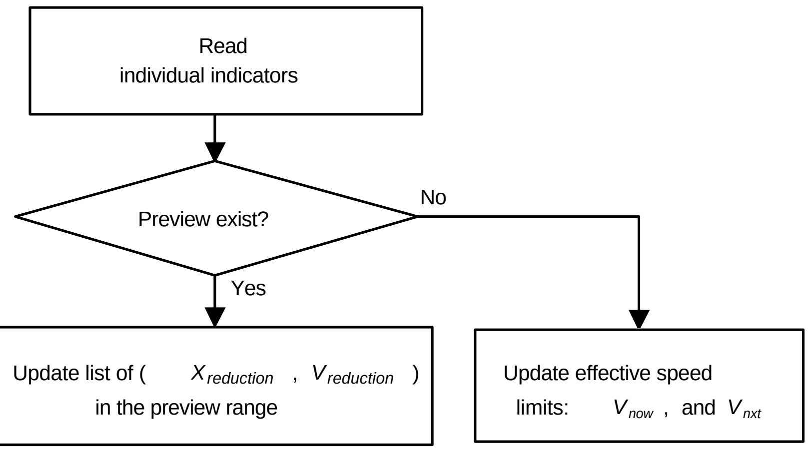


Figure O-2. Decomposition of *Perception*. $V_{reduction}$—the speed limit in the preview range that is below the current speed of the train. $X_{reduction}$—the distance from the current location of the train to the $V_{reduction}$.

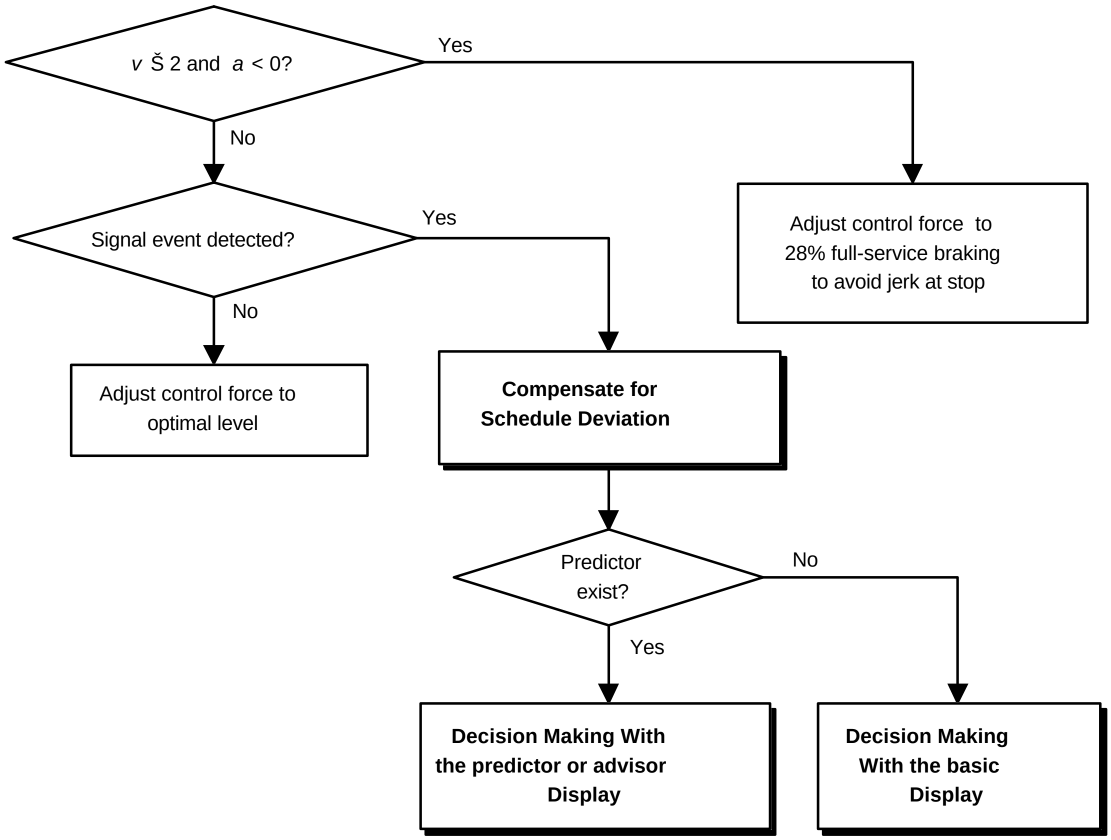


Figure O-3. Max-Max Control Decision Making. *v*—current speed of the train. *a*—current acceleration of the train. Preservation of ride quality is shown in this diagram. Just the moment before the train stops, the braking force should be reduced to a level below 30% of the full-service braking to preserve good ride quality. A 28% full-service braking was implemented in the model, as shown in this figure and Figure O-8.

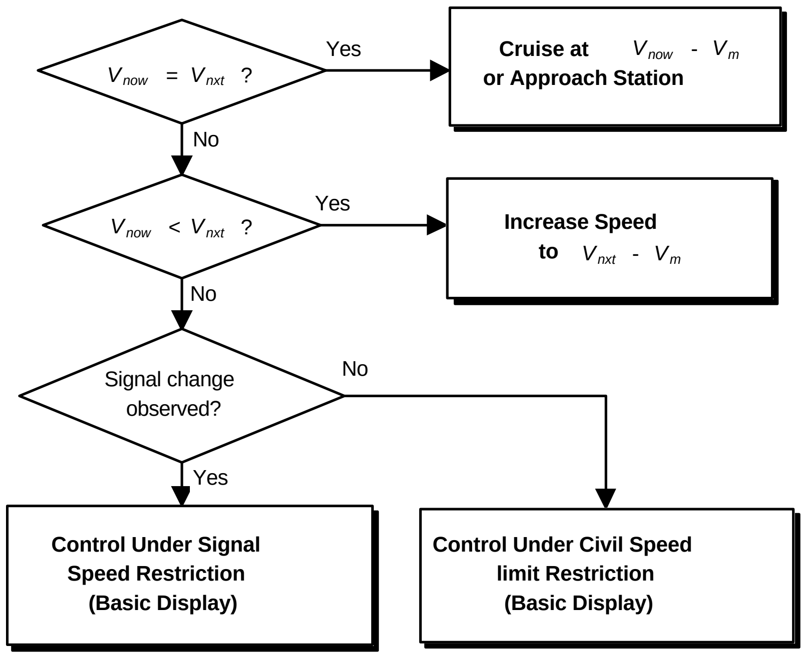


Figure O-4. Control Decision Making With the Basic Display. V_m—the margin speed by which amount the train cruises under the speed limit. V_{now}—speed limit of the current block. V_{nxt}—speed limit of the next block.

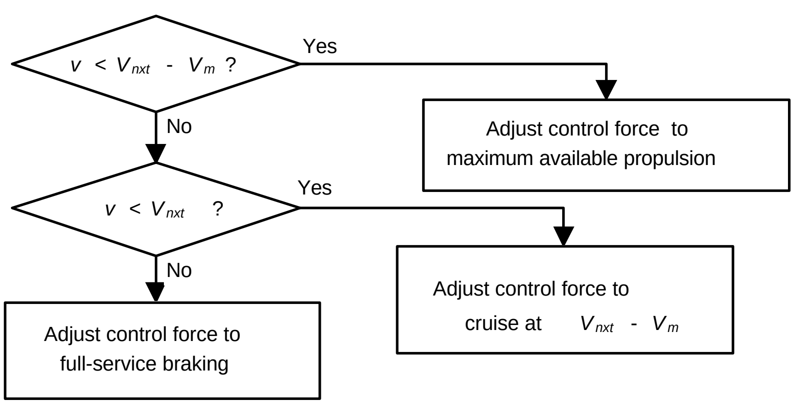


Figure O-5. Control Under Signal Speed Restriction (with the basic display). V_m—the margin speed by which amount the train cruises under the speed limit. V_{nxt}—speed limit of the next block.

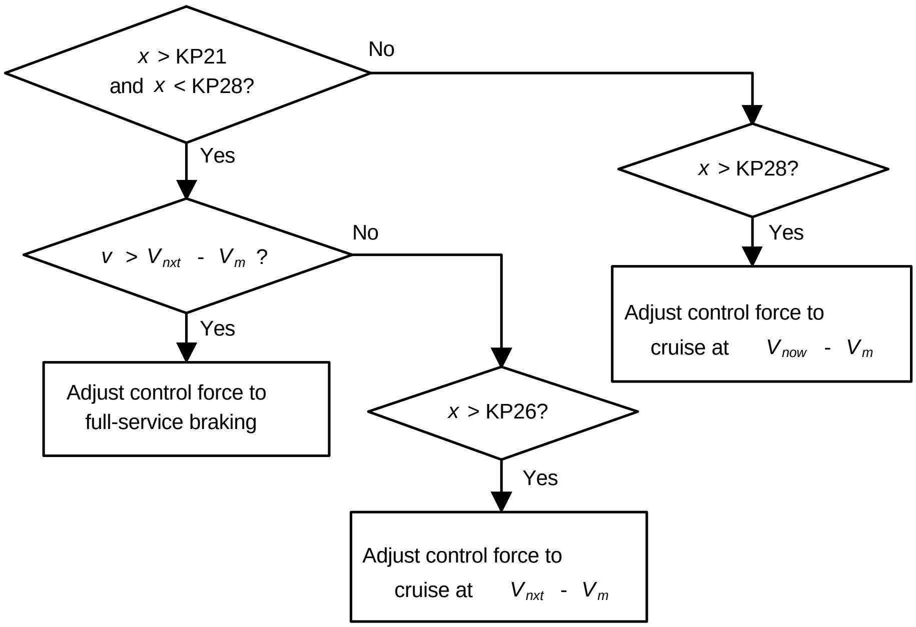


Figure O-6. Control Under Civil Speed Restriction (with the basic display). V_m—the margin speed by which amount the train cruises under the speed limit. V_{now}—speed limit of the current block. V_{nxt}—speed limit of the next block. KP—kilometer post.

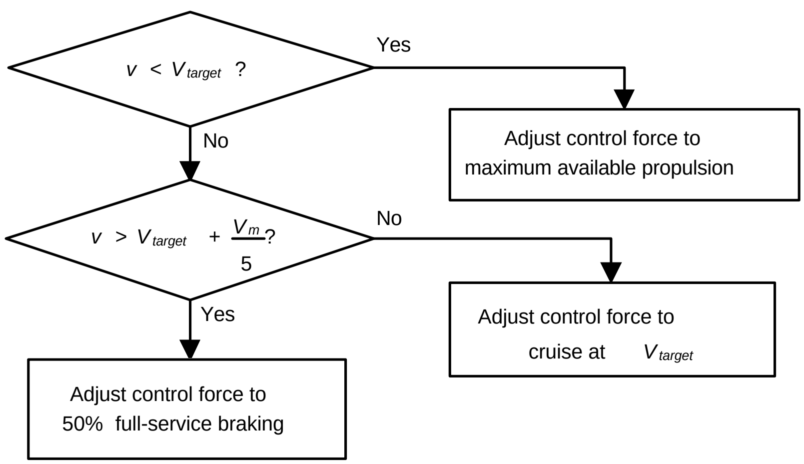


Figure O-7. Increase Speed to a Given Level V_{target}**.** V_m—the margin speed by which amount the train cruises under the speed limit.

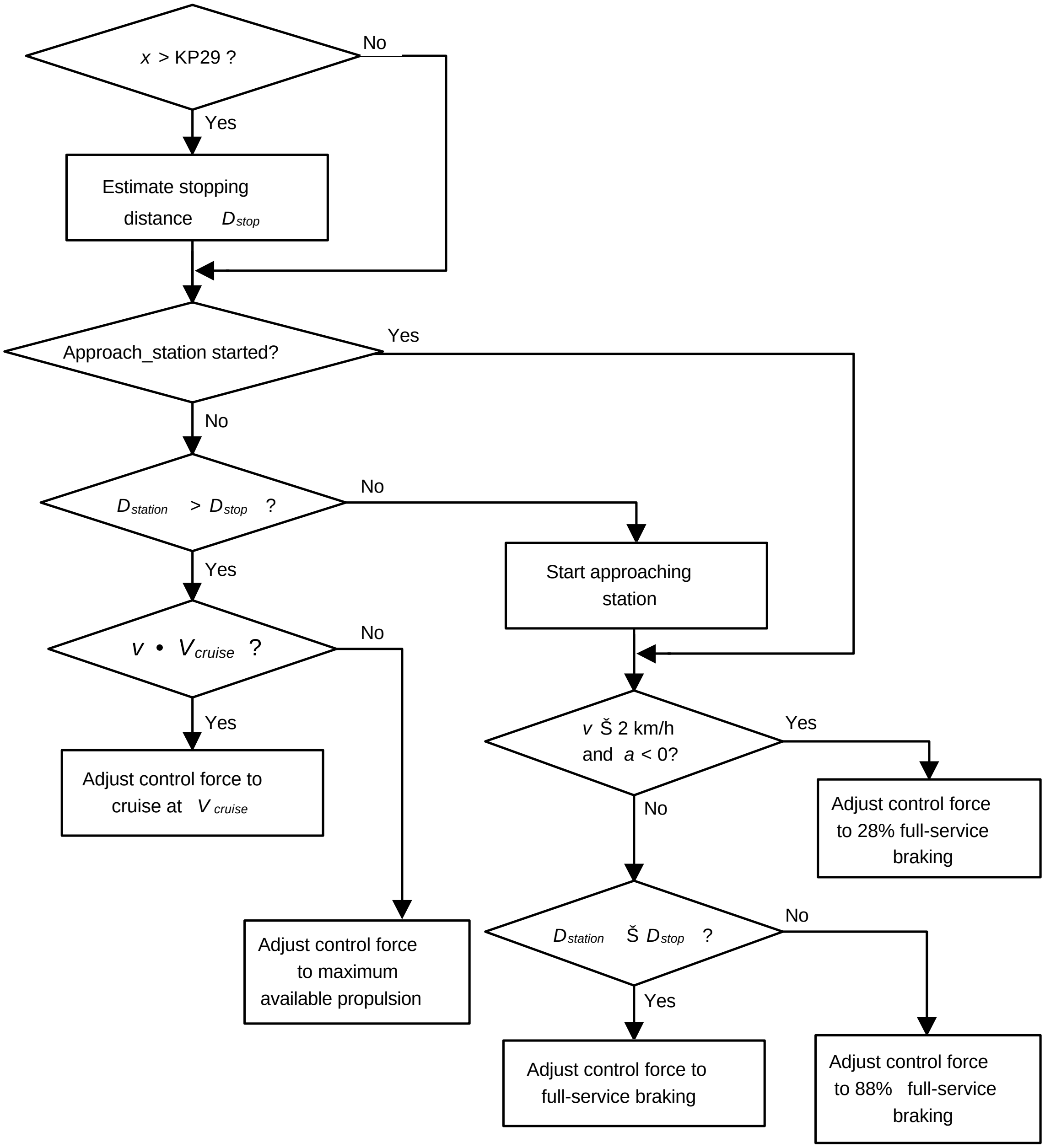


Figure O-8. Cruise at a Given Speed V_{cruise} **or Approach Station.** $D_{station}$—the distance to the destination station. D_{stop}—current stopping distance. v—current speed of the train. a—current acceleration of the train. Preservation of ride quality is shown in this diagram. Just the moment 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 this figure and Figure O-3.

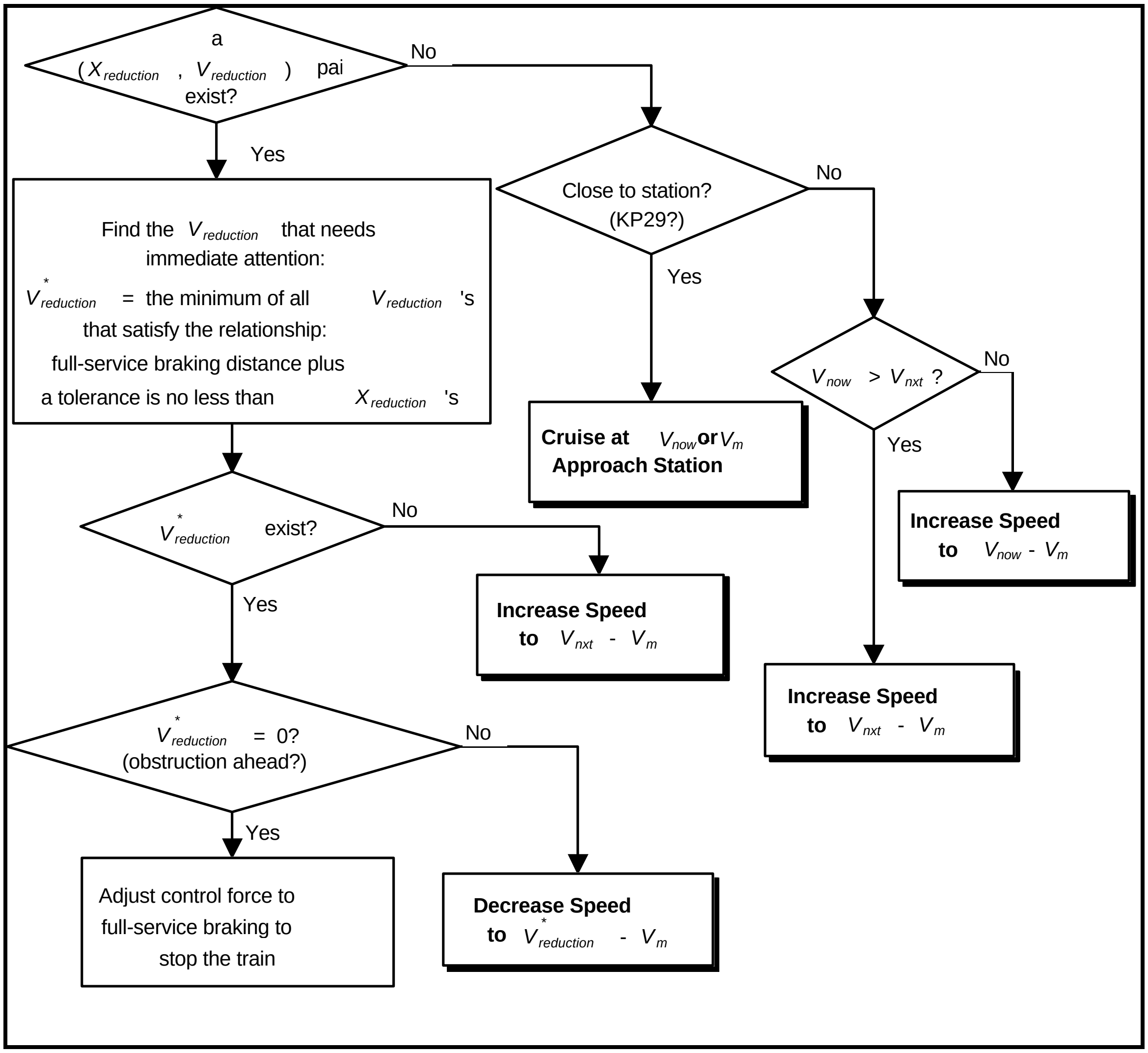


Figure O-9. Decision Making With the Predictor Display. V_{now}—speed limit of the current block. V_{nxt}—speed limit of the next block. $V_{reduction}$—the speed limit in the preview range that is below the current speed of the train. $X_{reduction}$—the distance from the current location of the train to the $V_{reduction}$. KP—kilometer post.

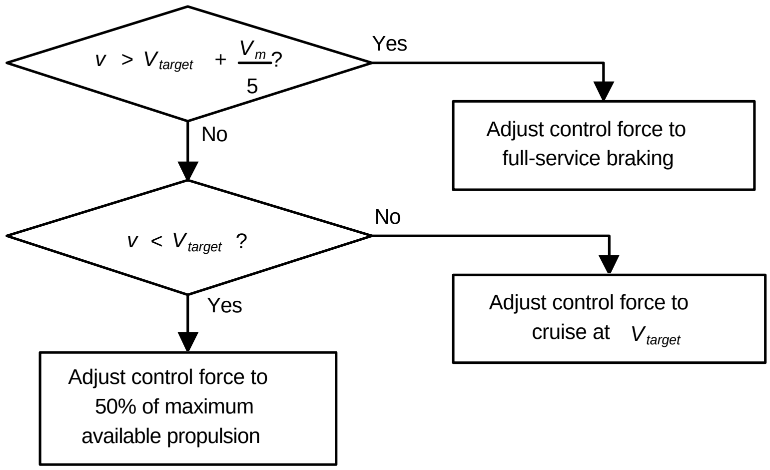


Figure O-10. Decrease Speed to a Given Level V_{target}.

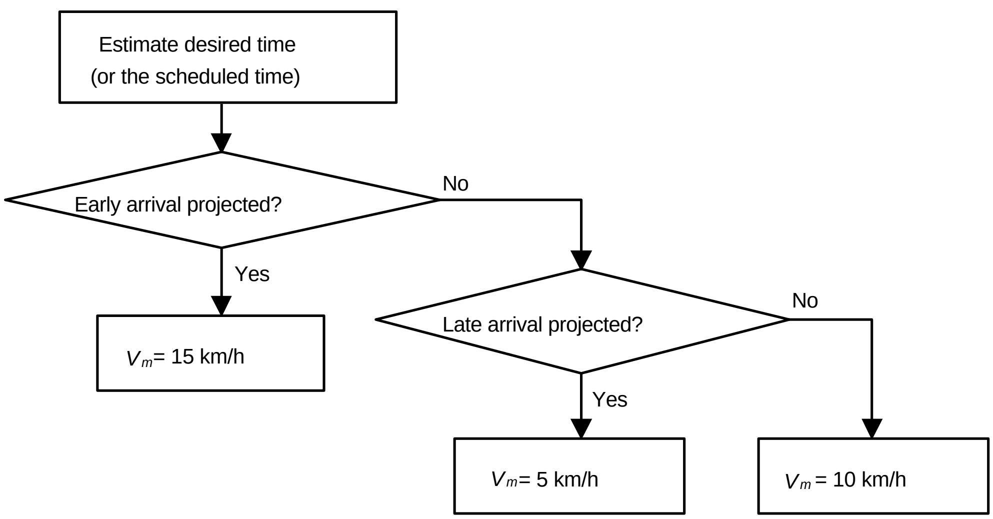


Figure O-11. Compensation for Schedule Deviation. V_m—speed, number of km/h that the train cruises below the speed limit. The rule for schedule adjustment shown here needs some explanation. If the train is on schedule (i.e., behind by less than 8 sec or ahead by less than 10 sec), the speed at which 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 the 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.