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Effects of Supervisory Train Control Technology on Operator Attention

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13. ABSTRACT (Maximum 200 words)

This report describes an experiment evaluating the effects of supervisory control automation on attention allocation while operating a train. The study compared two levels of supervisory control (partial and full) to manual control, in terms of how it affects vigilance detection and situation awareness. Human performance was measured using a human-in-the-loop train simulator. To evaluate vigilance, participants were asked to detect two types of automation failures and react to obstructions on the track. Situation awareness was measured using the Situation Awareness Global Assessment Technique (SAGAT) in which the simulation was suspended at periodic intervals and the subjects answered questions about the system. These answers were compared to objective measures of system performance.

Attention allocation varied with the method by which supervisory control was implemented. In particular, attention allocation for speed control, a critical piece of information, varied with the two methods. Partial supervisory control, as implemented in this experiment, resulted in a narrowing of attention. The primary focus was on speed information. By contrast, use of full supervisory control resulted in participants spreading their attention more broadly, but at the expense of speed information.

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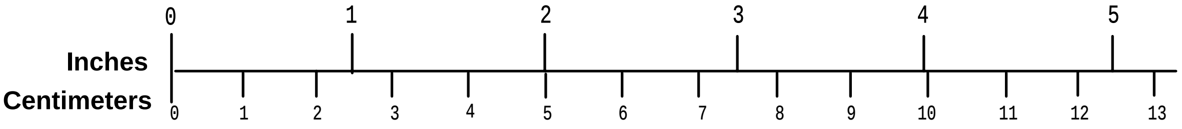

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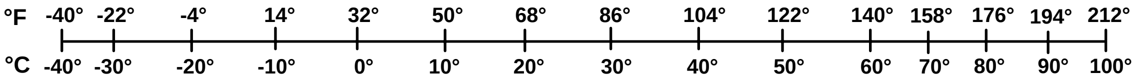

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Increasing train speed makes it more difficult for the train crew to see the wayside signals and respond in an appropriate and timely manner. As train speed increases, less time is available for the locomotive engineer to react, due to the increased distance required for the vehicle to decelerate. Train control technology (i.e., positive train control) has been proposed as a way to compensate for the physical and perceptual limitations of the operator. One type of train control that has been proposed is supervisory control. In supervisory control, the train control system operates the train and the locomotive engineer monitors the train control system. However, studies of supervisory control show that it has negative as well as positive effects on human performance.

This study examined the impact of supervisory train control on two aspects of attention, vigilance, and situation awareness. High-speed train operations were simulated in a human-in-the-loop train simulator. Two kinds of supervisory train control: full and partial were compared to manual control. To evaluate attention allocation in train handling, participants operated a train during which equipment failures occurred at very low frequencies and vehicles obstructed the track. The ability of participants to respond to these events was measured. Situation awareness was measured by suspending the simulation periodically to obtain information from the participant regarding his or her knowledge related to train handling. The participant's answers were compared to objective information about the locomotive's state.

The study documented in this report was part of a program to examine human factors issues related to the introduction of new train control technology in high-speed rail operations. The Federal Railroad Administration sponsored this work as part of its activities to develop Intelligent Railroad Systems (Federal Railroad Administration, 2002).

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EXECUTIVE SUMMARY

As high-speed passenger operations are adopted in the United States, train control technology is required to enable the train crew to operate the train safely. As train speeds increase, the locomotive engineer has less time to acquire information needed to operate the locomotive and respond. In high-speed rail operations, train control technology using decision support aids, supervisory control, or some combination has been proposed as a means to compensate for the sensory, perceptual, and cognitive limitations of the locomotive engineer.

This study focused on the impact of supervisory train control technology on human performance. The successful application of supervisory control in train operations requires an understanding of how it affects the train crews that interact with this technology. For example, locomotive engineers often work long hours with inadequate amounts of rest between shifts (Thomas, Raslear, and Kuehn, 1997). As a result, engineers can become less attentive over the course of their shift. Supervisory train control technology has been proposed to assist the locomotive engineer in operating the locomotive safely during high speeds over long periods.

However, supervisory train control may change how the locomotive engineer allocates his or her attention. The question is how do these changes affect the operator's performance and what are the safety implications of these changes? To control the train, the engineer collects information both inside and outside the cab. Inside the cab, the engineer monitors locomotive health by monitoring visual displays, listening to the sounds made by the locomotive and on-board equipment, and attends to kinesthetic cues (i.e., vibrations). Outside the cab, the engineer looks for hazards, monitors wayside signals, landmarks, and other visual cues needed to anticipate future train movements. The skills and knowledge needed to operate a train are built up over time as the engineer learns how to control the train and learns the physical attributes of the territory over which he will operate. Likewise, the engineer learns how to effectively allocate his attention between events inside and outside the cab so that the train operates safely and efficiently.

How do the locomotive engineer's attention allocation strategies change when supervisory train control technology is introduced? What are the safety implications of these changes? For example, a key issue in supervisory control is whether the operator can detect train control failure and take over safe operation of the train. In relying on supervisory control, the engineer’s ability to intervene promptly in case of an unexpected event can deteriorate (Huey and Wickens, 1993). How does supervisory control affect the engineer’s ability to detect unexpected events? What happens when equipment unrelated to the train control system fails? Detecting a train control failure itself may also be a challenge for the operator. This study will address these questions using two paradigms: vigilance and situation awareness. Both concepts can be used to examine how shifts in attention affect human performance.

Vigilance refers to the capacity of the human operator to sustain attention and remain alert to stimuli over a prolonged time. The most significant aspect of the vigilance decrement is that it arises from searching for a relatively infrequent signal over a prolonged period (Dember and Warm, 1979).

Very few vigilance studies have been performed with a very low target rate on the order of one target per 30 minutes (Molloy and Parasuraman, 1996; Loeb and Binford, 1970). Lanzilotta (1995) examined the effects of supervisory train control on vigilance in a locomotive simulator

and found that operators show more variability in detecting train control failures with partial supervisory control than full supervisory control. He concluded that with partial supervisory control, observers exhibited a greater tendency to attend to events outside the locomotive cab than with full supervisory control. However, in this study the number of failures on each trip (6) may have affected the detection performance of the participant. What would happen in a system in which the number of failures was smaller? The current study examined this question measuring participant’s ability to detect a small number of failure events. Instead of six events per trip found in Lanzilotta's study, participants were exposed to only two events per trip.

Situation awareness (SA) is a broader concept than vigilance. Endsley (1993) defines SA as

> “*the perception of the elements of the environment within a volume of time and space, the comprehension of their meaning and the projection of their status in the near future.*”

In locomotives with supervisory train control, the engineer can become a passive processor of information. The engineer needs to know what the train control is doing as well as what the other components are doing. However, feedback in train control systems can be inadequate. This loss of information can make it difficult to detect train control failures and intervene when failures occur.

In Lanzilotta's study examining the effect of supervisory train control on situation awareness, there was an inverse relationship between situation awareness and the level of supervisory control. As the level of supervisory control increased, situation awareness degraded. Perceived situation awareness was highest in the condition where the operator controlled the train manually and was lowest in the full supervisory control condition. However, in this study, situation awareness was measured by asking participants to rank the train control modes by their perceived level of situation awareness. This subjective measure may not give an accurate measure of situation awareness as the response may be affected by the outcome of the experimental trials. An objective method that compares an operator's knowledge of the system while it is being operated with information about the actual state of the system may give a more representative picture of the level of situation awareness. The current study used such a method developed by Endsley (1995b) to evaluate the level of situation awareness for different kinds of train control.

Three control modes for the operation of the train were evaluated: manual, partial supervisory, and full supervisory control. The three control modes represent the range of control modes found in current railroad operations. Under manual control, the human was solely responsible for controlling the speed of train, while in partial supervisory control the human operator set the desired speed (i.e., cruise control) and the train control system was responsible for achieving and maintaining it. Operation of the vehicle under full supervisory control normally required no human intervention, as the train control system was programmed to respond to the appropriate signals.

A laboratory experiment, using a human-in-the-loop locomotive simulator, was conducted to examine the effects of three control modes on operator attention. A series of events both inside and outside the locomotive were presented to participants during the course of operating the train and the ability to detect these events was measured. The participant's task was to control the vehicle speed according to the signal and civil speed limits indicated in each block, look out for potential hazards, and respond to them in an appropriate manner. During the course of the experiment, the simulation was interrupted and the participants were questioned about their knowledge of the locomotive's health and its track position.

To measure vigilance, two types of equipment failure and an obstruction were introduced. The failures remained active for a set period, unless detected and reset by the participant. If not reset by the participant within the specified time interval, the failure was automatically reset. The amount of time to complete a round trip (45 minutes) was broken down into three equal time blocks and the detection rate was measured in each block. The percentage of failures detected by the participants in each time block was used as a measure of vigilance (Molloy and Parasuraman, 1996) inside the cab. Outside the cab, vigilance was measured by the distance from the obstruction where the train stopped. To measure situation awareness, Endsley's Situation Awareness Global Assessment Technique (SAGAT) was used (1995b). In this method, the simulation was paused and the displays were blanked at periodic intervals. The participant was asked several questions about the status of the locomotive's operating condition and its position on the track.

Overall, supervisory train control systems improved situation awareness and vigilance performance compared to manual operation. However, differences in the way the supervisory control systems operated contributed to differences in attention allocation. These differences were greatest for unexpected events such as equipment failures and obstructions at highway-railroad grade crossings. A signal detection analysis indicated that the supervisory control system influenced the observer’s response strategies, but not perceptual sensitivity in detecting equipment failures. There were no differences in sensitivity between the three control modes. By contrast, participants in the partial supervisory control condition exhibited a tendency similar to the manual control condition, to say in-cab failures did not occur, while the participants in the full supervisory control condition exhibited a slight preference to say an in-cab failure did occur.

While participants relied upon the system for routine speed control decisions, participant had to intervene when an event outside the scope of the train control system (i.e., an obstruction on the track) occurred. They responded by deactivating the supervisory control system and taking over active control of the train. Although the participant may have detected the obstruction as far away as in the manual mode, making a decision about the proper amount of braking was delayed while speed information was gathered. Compared to the manual control condition, more time was required to understand the situation. This finding is consistent with Wickens and Kessel’s (1979) research showing that observers were better at detecting a sudden change in system state when manually controlling the system than when monitoring the system.

The challenge for developers of train control systems is learning how to design the interface so the operator remains actively engaged in safety critical tasks. Attention to activities directly related to train movement is critical to safe operation. However, using technology in a way that degrades the direct involvement of the operator with the system can make it more difficult to detect and recover from errors (Huey and Wickens, 1993). This degradation in safety critical aspects of their performance was also reflected in the participant’s response to questions about workload and stress. Participants rated the full supervisory condition as having the lowest workload, but the highest stress. These comments indicated their discomfort with not being actively engaged in a safety critical aspect of the train operation.

The partial supervisory control mode method for assisting with speed control showed some similarity with the full supervisory control system in its impact on attention allocation. Like the supervisory control mode, this control mode resulted in participants monitoring events such as bearing temperature, traction motor status, and block location better than in the manual mode. It also showed an important difference from the full supervisory control mode. Unlike the full supervisory control mode, speed awareness performance was better in the partial supervisory control mode than in the manual mode. The need to allocate more attention resources to speed was attributed by the participants to their difficulty in setting the desired speed.

The results of this experiment indicate that supervisory control systems can impact operator performance in non-intuitive ways. The two types of supervisory control in this study both controlled speed, but they affected human performance differently. The complex relationship between supervisory control systems and human performance, suggests the need for human-in-the-loop testing to evaluate new train control systems for their impact on human performance before they are implemented in revenue service. Human-in-the-loop testing of supervisory control systems can identify the likely human errors. Through an iterative design process and training, some of these errors may be eliminated. For errors that cannot be eliminated, designers can facilitate recovery by making actions reversible and creating warnings to alert the operator when they occur.

1. INTRODUCTION

The era of high-speed passenger rail service in the United States began with the service on the Northeast Corridor. High-speed rail service plays a central role in mass transportation systems in Europe and Japan. Examples include the German Inter-City Express (ICE), the French Train à Grand Vitesse (TGV), and the Japanese Shinkansen.

However, there are safety implications that arise from speed increases that affect locomotive engineer performance. First, as train speeds increase, the locomotive engineer has less time to acquire information needed to operate the locomotive and respond. A study conducted in France found that the maximum speed for accurate perception of wayside signals was 137 mph (220 km/h) (Askey, 1995). Second, as speed increases, the locomotive engineer has less time to slow or stop the train and must decide to slow or stop the train earlier, due to the increased stopping distance. As train speed increases beyond the perceptual and cognitive limits of the locomotive engineer, the locomotive cannot be safely operated without assistance.

Train control technology can provide this assistance to the engineer. In high-speed rail operations, train control technology using decision support aids, supervisory control, or some combination has been proposed as a means to compensate for the sensory, perceptual, and cognitive limitations of the locomotive engineer. The use of train control technology can be divided into two approaches:

Decision aids. Decision support aids provide information to assist the engineer in train control. In such an approach, the locomotive engineer makes decisions regarding vehicle operation and actively controls the vehicle. Askey (1995) looked at the use of different levels of decision aids to help the engineer in train control operations. She found that decision aids improved safety by reducing time needed to respond to emergency events and by reducing the need for emergency braking.

Supervisory control. In this approach, all necessary information for vehicle operation is passed to the control system that is responsible for operating the train according to prescribed rules. The locomotive engineer’s role shifts to that of a supervisor who monitors the proper functioning of the control system.

The type of train control used in the current operational high-speed rail systems (ICE, TGV, Shinkansen) varies by country. According to Sheridan, Lanzilotta, and Askey (1994): “The German philosophy (ICE) of rail development emphasizes supervisory control with use of the human as a system monitor, while the French (TGV) and Japanese (Shinkansen) depend more on the human for control decisions.”

This study focused on the impact of supervisory control on locomotive engineer performance. The successful application of supervisory control in train operations requires understanding how it will affect the engineers who interact with this technology. For example, locomotive engineers may work long hours with inadequate amounts of rest between shifts (Thomas, Raslear, and Kuehn, 1997). Trains cover large distances and locomotive engineers must attend to tasks over prolonged periods. As a result, operators can become less attentive over the course of their shift. A supervisory control system could protect against the sleeping driver, but could create new problems related to attention allocation.

Supervisory control may also change how the locomotive engineer allocates his or her attention. The question is how do these changes affect the operator's performance and what are the safety implications of these changes? To operate the train, the engineer acquires information inside and outside the cab. Inside the cab, the engineer monitors locomotive health by monitoring visual displays, listening to the sounds made by the locomotive and on-board equipment, and attends to kinesthetic cues (i.e., vibrations). Outside the cab, the engineer looks for hazards, monitors wayside signals, landmarks, and other visual cues needed for anticipating future train movements. The skills and knowledge needed to operate a train build up over time as engineers learn how to control the train and the physical attributes of the territory over which they operate. Likewise, engineers learn how to effectively allocate attention between events inside and outside the cab so that the train operates safely and efficiently.

How do the locomotive engineer's attention allocation strategies change when supervising train control systems? What are the safety implications of these changes? For example, a key issue in supervisory control is whether the engineer can detect equipment failure and take over safe control of the train. In relying on supervisory control, the engineer’s ability to intervene promptly in case of an unexpected event can deteriorate (Huey and Wickens, 1993). How does supervisory control affect the engineer’s ability to detect unexpected events? This study will address these questions using two paradigms: vigilance and situation awareness. Both concepts can be used to examine how shifts in attention affect human performance.

Vigilance

Vigilance refers to the capacity of the human operator to sustain attention and remain alert to stimuli over prolonged periods. Vigilance studies originated during World War II when the Royal Air Force (RAF) commissioned Norman H. Mackworth (1961) to study the radar observers’ decrement in detection rate of enemy submarines. He discovered that a vigilance decrement occurred after only 30 minutes. The most significant aspect of the vigilance decrement was that it arose from searching for a relatively infrequent signal over a prolonged period of time (Dember and Warm, 1979).

While vigilance has been studied extensively in the context of laboratory tasks, relatively few studies have been performed in environments that closely simulate actual work settings, the main reason being the difficulty of applying signal detection theory. An important question is the extent to which data from laboratory tasks can be extrapolated to operational tasks because of the event rate used. For the majority of vigilance studies, a target rate of 1 target per minute is considered low. However, in an operational setting, “events” that need to be distinguished and acted upon, such as failures, occur much less frequently. Few studies have been performed with a very low target rate on the order of 1 target per 30 minutes (Molloy and Parasuraman, 1996; Loeb and Binford, 1970). Lanzilotta (1995) examined the effects of supervisory control on vigilance in a human-in-the-loop locomotive simulator and found that operators showed more variability in detecting equipment failures with partial supervisory control than full supervisory control. He concluded that with the partial supervisory control, observers exhibited a greater tendency to attend to events outside the locomotive cab than with full supervisory control. However, in this study the number of failures on each 45-minute trip (6) may have affected the participant’s detection performance (1 failure per 7.3-minute period). What would happen in a system in which the number of failures was smaller? The current study examined this question using a small number of failure events. Instead of 6 events per 45-minute trip found in

Lanzilotta's study, participants were exposed to only 2 events per 45-minute trip (1 failure per 22.5-minute period).

Situation Awareness

Situation awareness (SA) is a broader concept than vigilance. Endsley (1993) defines SA as

> "*the perception of the elements of the environment within a volume of time and space, the comprehension of their meaning and the projection of their status in the near future*."

For the locomotive engineer, situation awareness represents the operator's mental model of the state of the system. Endsley proposed that this mental model could exist at several levels. First, the engineer must perceive the system status. Second, the perceived information must be integrated and compared to the operational goals of the system to provide comprehension. Third, the operator uses understanding of the system to predict future events and enabling proactive behavior. In locomotives with supervisory control systems, the engineer can become a passive processor of information. The engineer needs to understand what the train control system is doing. However, feedback in supervisory control systems is frequently inadequate. This loss of information can make it difficult to detect control failures and take over control when failures occur.

In Lanzilotta's study examining the effect of supervisory train control on situation awareness, there was an inverse relationship between situation awareness and the amount of supervisory control. As the level of supervisory control increased, situation awareness degraded. Perceived situation awareness was highest in the condition where the operator controlled the train manually and was lowest in the full supervisory control condition. However, in that study, situation awareness was measured by asking participants to rank the supervisory control modes by their perceived level of situation awareness. This subjective measure may not give an accurate measure of situation awareness as the response may be affected by the outcome of the experimental trials.

An objective method, that compares an operator's knowledge of the system while it is being operated with information about the actual state of the system, may give a more representative picture of situation awareness. The current study used such a method developed by Endsley (1995b) to evaluate the level of situation awareness for different levels of supervisory train control.

Endsley's (1995b) method is called Situation Awareness Global Assessment Technique (SAGAT). In this method, participants answer questions about their current perceptions of the situation at randomly selected times during the simulation. The simulation is suspended and the displays are blanked while the participant answers questions. After the simulation has ended, answers to the experimenter's questions are compared to the real situation as measured by the computer simulation to provide an objective measure of situation awareness.

To summarize, the purpose of the current research was to determine the implications of supervisory train control in high-speed train operations with regard to vigilance monitoring and situation awareness. Using a human-in-the-loop locomotive simulator, train control failures were introduced to learn how quickly operators could detect the failures when the number of events requiring action by the operators was very low for different levels of supervisory control.

Situation awareness measurements were collected during the simulation, using the SAGAT developed by Endsley.

Three train control modes were evaluated: manual, partial, and full supervisory control. Under manual control, the operator actively controlled the train. Under partial supervisory control, the human operator set the desired speed (i.e., cruise control) and the train control system was responsible for achieving and maintaining it. Under full supervisory control, no human intervention was required as the train control system was programmed to adjust train speed in response to the appropriate signals and civil speed limits.

2. METHOD

Overview

A laboratory experiment, using a human-in-the-loop locomotive simulator, was conducted to examine the effects of three train control modes on operator attention. Specifically, the experiment examined the effects of train control in the situation where action by the engineer was not required for a long period (low event rate). As part of this study, two levels of supervisory train control (full supervisory control, partial supervisory control), and manual control operation were evaluated for their effects on vigilance and situation awareness. A series of events inside and outside the locomotive were presented to participants while operating the train and the ability to detect these events was measured.

To measure vigilance, two types of train control failure and an obstruction were introduced. The failures remained active for a set period, unless detected and reset by the participant. If not reset by the participant within the specified time interval, the failure was automatically reset. The time to complete a round trip (45 minutes) was broken down into three 15-minute blocks and the detection rate was measured in each block. The percentage of failures detected by the participants in each time block was used as a measure of vigilance (Molloy and Parasuraman, 1996) inside the cab. Outside the cab, vigilance was measured by the distance from the obstruction where the train stopped.

To measure situation awareness, Endsley's Situation Awareness Global Assessment Technique was used (1995b). In this method, the simulation was paused and the displays were blanked at periodic intervals. The participant was asked several questions about the status of the locomotive's operating condition and its position on the track.

Experimental Design

The independent variable was train control mode. There were two types of supervisory control and one type of manual control as shown in Table 1. All participants were exposed to all train control conditions.

Table 1. Train Control Condition

Type of Train Control
Full Supervisory
Partial Supervisory
Manual

To counterbalance possible learning effects across participants, each participant was introduced to the control modes in the order shown in Table 2. To encourage the participant to perform according to the objectives of the experiment, an incentive system was implemented. Points were awarded or taken away according to the bonus and penalty schedule described in Appendix A. Points were converted to monetary rewards at a rate of one dollar per 1000 points.

Table 2. Presentation Order of Train Control Modes

Participant	Presentation order		
	1	2	3
1	Full Supervisory	Manual	Partial Supervisory
2	Full Supervisory	Partial Supervisory	Manual
3	Manual	Partial Supervisory	Full Supervisory
4	Manual	Full Supervisory	Partial Supervisory
5	Partial Supervisory	Full Supervisory	Manual
6	Partial Supervisory	Manual	Partial Supervisory

Failure Detection

To assess vigilance performance inside the cab, two types of equipment failures were introduced. Appendix C shows the track position where the failures occurred.

Motor failure. Under normal operating conditions, electric current flowed through each of four motors when thrust was applied. The ammeters gauge displayed the amount of current flowing through each motor. A motor failure occurred when current failed to flow through one of the motors, indicated on the ammeter gauge. If the participant detected a motor failure, the participant was instructed to remove power from all the motors by pulling the control lever back to the braking position, press the appropriate key for resetting the failure, and resume operation. A motor failure lasted 12 seconds unless reset by the participant. If the participant failed to reset the motor failure within that time, the system was automatically reset.

Bearing failure. In principle, bearing temperature normally follows the speed of the train with some time lag, but never rises above a threshold (131^{o} F) for safety reasons. In practice, the bearing temperature fluctuated around a mean value, depending on the average speed of the vehicle. When a bearing failed, the temperature increased at a rate almost double the maximum rate regardless of the train’s speed. Detecting a bearing failure required the participant to observe this abnormal temperature change. The participant was instructed to press a reset key to correct the bearing failure. The bearing failure lasted 20 seconds unless reset by the participant. If the participant failed to reset the bearing failure within that time, it was reset automatically.

Within each combination of control mode and time block nine equipment failures occurred. With nine combinations of control mode and time block, 81 equipment failures occurred. Appendix D shows the responses made to the equipment failures and obstructions for each participant. The average number of failures (motor or bearing) for a round trip was two, one for each type of failure.

Bonus points were awarded for detecting and resetting the failures. Penalty points were given for pressing the reset key when no failure existed. The incentive system is described in Appendix A.

Obstruction Detection

There were five grade crossings in this experiment. At each grade crossing, highway motor vehicles could cross in front of the train from either direction. These motor vehicles were visible at over 0.3 miles (0.5 km) from the train. Each block containing grade crossings had a civil speed limit of 62-mph (100 km/hr). Traffic at the grade crossings arrived according to a probabilistic process. A car would proceed across the crossing only if there was sufficient distance to clear the crossing before the train arrived. However, it was possible for a car to become disabled as it was crossing the tracks, which would obstruct the track. The participant was instructed to bring the train to a complete stop before the intersection if a disabled motor vehicle was detected. If the participant could not avoid a collision, a crack appeared on the locomotive cab window. The crack remained on the window for the remainder of the trip.

It was important for the participant to quickly determine whether the train should stop or proceed. The participant had to balance the consequences of a collision with the costs of schedule delays due to braking the train. It was up to the participant to evaluate the situation and determine the best course of action. This type of emergency was used to assess the effects of train control in attending to events outside the locomotive.

If the participant collided with an obstruction, the participant was instructed to stop the train and notify the dispatcher. The participant then continued on the trip. The cracked window remained displayed for the remainder of the trip. The participant was awarded points for detecting and avoiding the hazard according the schedule shown in Appendix A.

Situation Awareness

Situation awareness was measured using a technique developed by Endsley (1995b), whereby the simulation was temporarily paused while the experimenter asked the participant questions about the state of the train and its position. While the simulation was paused, the out-the-window view and instrument panel appeared blank. The train remained in the same position until the question and answer session was completed. The participant then resumed operating the train at the same speed and position at which the simulation was paused. The experimenter asked the participant to give answers about the train's position with respect to block number, milepost, train speed, and bearing temperature.

Two measures were used to assess situation awareness: percent of correctly answered questions or Mean Absolute Error (*MAE*). *MAE* is a measure of deviation between the participant’s response and the actual state of the variable. It was defined as:

$$MAE = \sum_{i=1}^{n} \frac{| x - \hat{x} |}{n}$$

where x was the participant's response, $\hat{x}$ was the actual value and n was the number of participants. Speed and bearing temperature were calculated using MAE. For motor current, block number and milepost answers were classified either as correct or wrong and reported as a percent of the correct answers.

Participants

Fifteen people participated in the experiment. Twelve participants were undergraduate or graduate students at the Massachusetts Institute of Technology (MIT). The remaining three participants were people who responded to notices placed on the MIT campus requesting participation in the experiment. Two students participated in a pilot study for fine-tuning the experiment, while the remaining 13 participated in the actual experimental trials. Data from one participant was thrown out after inspection showed that he repeatedly failed to comply with speed limits. Each participant was paid $10 per hour.

Facilities: High-Speed Locomotive Simulator

The High-Speed Locomotive Simulator was a real-time human-in-the-loop locomotive simulator developed to conduct human factors research in high-speed rail operations. The computer hardware consisted of two Silicon Graphics (SGI) personal Iris Workstations, one SGI Indigo-2 workstation, an IBM compatible 486 computer, a Barco projector, and projection screen. The participant sat in the cab where the controls and instrument displays were located. Figure 1 shows the layout. The out-the-window view was displayed on a wall-mounted projection screen in front of the cab.

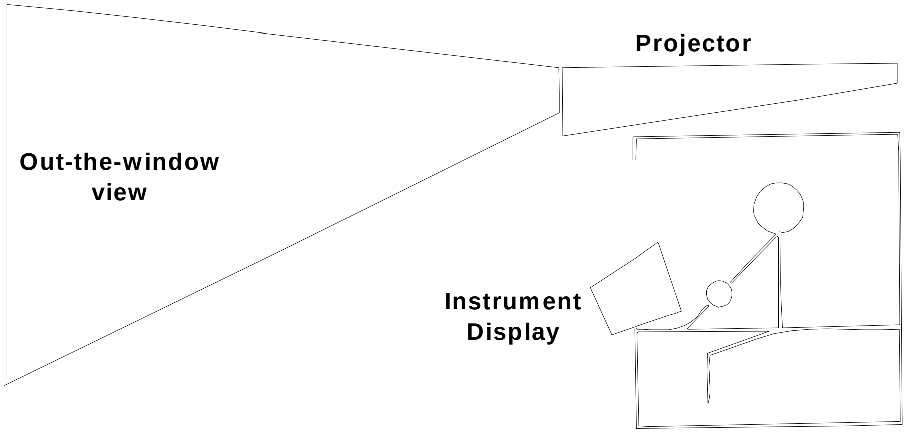
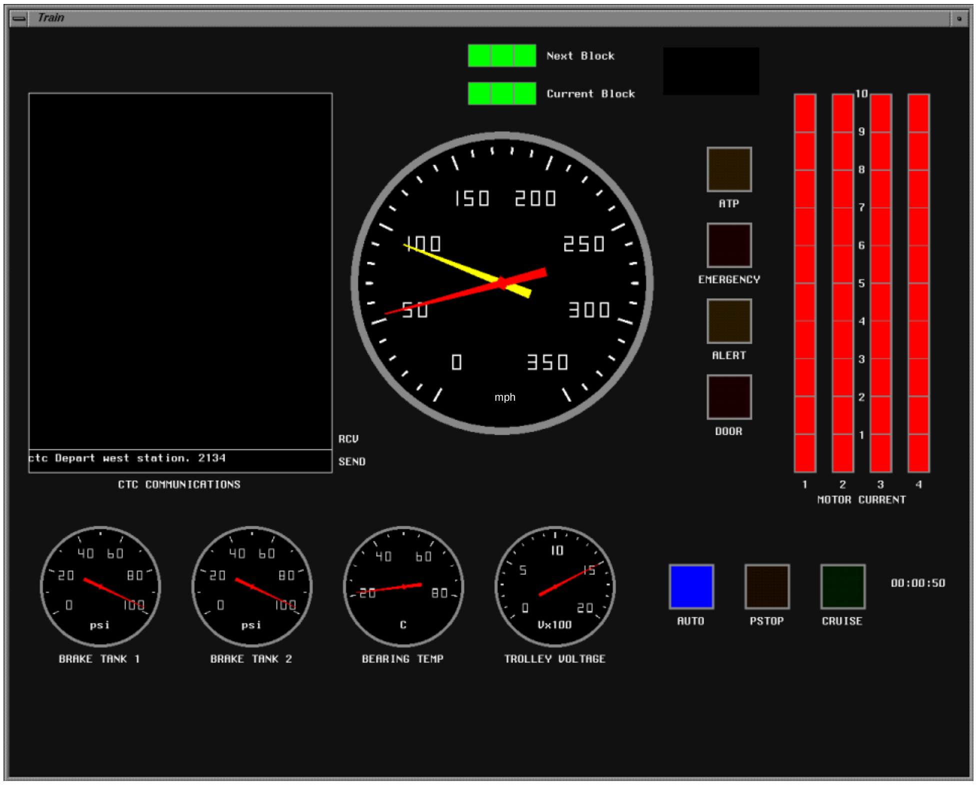


Figure 1. Train Simulator Layout

The operator controlled the locomotive’s speed with a lever that combined both throttle and brake functions. When the control lever was in the center (vertical) position, the train control was in neutral. Pushing the control lever forward away from the operator accelerated the train; pulling the lever toward the operator decelerated the train. The operator had push buttons to the left and right of the instrument display for controlling the emergency brake, alerter, bell, horn, and traction motors. The SGI Indigo-II workstation generated the out-the-window view as well as computing the vehicle dynamics that enable the operator to control the train. One personal Iris displayed the instrument panel shown in Figure 2, while the other personal Iris served as the dispatcher workstation. All three machines communicated with each other over a Local Area Network (LAN). Appendix B describes the features added to the locomotive simulator for this experiment.


Train
Next Block
Current Block
ATP
EMERGENCY
ALERT
DOOR
150
200
100
250
50
300
0
350
mph
10
9
8
7
6
5
4
3
2
1
1 2 3 4
MOTOR CURRENT
RCV
SEND
CTC COMMUNICATIONS
40 60
20 80
0 100
psi
BRAKE TANK 1
40 60
20 80
0 100
psi
BRAKE TANK 2
40 60
20 80
C
BEARING TEMP
10
5 15
0 20
Vx100
TROLLEY VOLTAGE
AUTO
PSTOP
CRUISE
00:00:50

ctc Depart west station. 2134

Figure 2. Instrument Panel

The simulator exhibited three control modes: manual control, partial supervisory control, and full supervisory control. In manual control, the operator was solely responsible for controlling the speed and the position of the vehicle using the combined control lever. The partial supervisory control system was designed to maintain a constant speed set by the operator. When operating the train in partial supervisory control mode, the operator set the desired speed. In this mode, the train control applied the proper amount of thrust to achieve and maintain the set speed. Partial supervisory control did not affect braking, so the operator had to apply the brakes manually when needed. In full supervisory control, speed control of the vehicle was exclusively assumed by the train control system, which was responsible for setting the speed in accordance to the speed limits of each block. Speed control included application of both the throttle and brakes. In both the full and partial supervisory control modes, manual application of the brakes by the operator disengaged the supervisory control system. The full supervisory control system controlled the speed of the vehicle without human intervention.

The territory in the experiment was comprised of two fictional stations, named East Station and West Station and a single track between the two stations, as shown in Figure 3. Thirty-one miles (50 km) of single track separated the two stations. Loops at the end of each station were used to reverse the vehicle's direction on the main track. One-way travel time from station to station was approximately 20 minutes. Travel time around the loops was almost 5 minutes. Hence, the round trip lasted roughly 45 minutes.

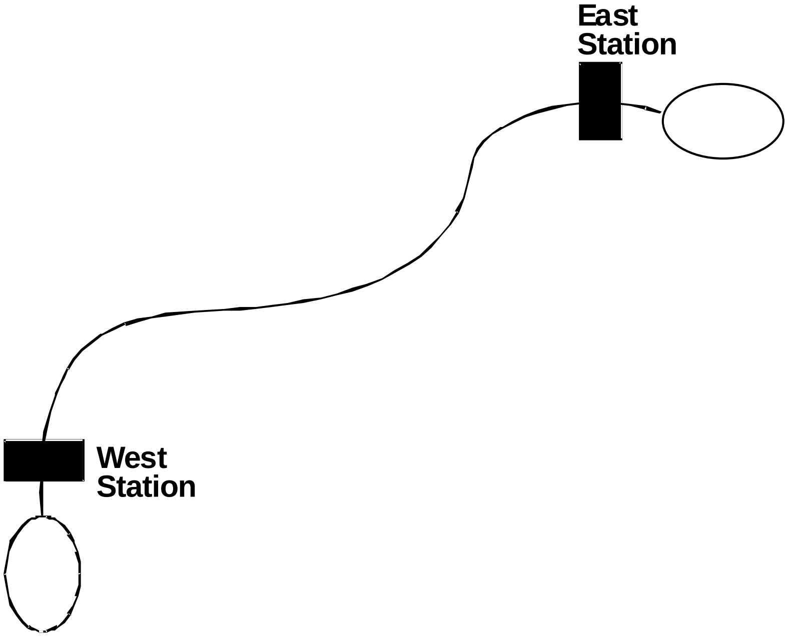


Figure 3. Track Layout

The current simulation used block signaling to communicate permission to occupy the track and speed limits. With block signaling, the track was divided into sections. In the current simulation, all blocks between stations were 1.24 miles (2 km), and all blocks in the loop sections were 0.62 miles (1 km) in length. A color-coded signal was located at each block boundary. This signal indicated the maximum speed permitted through the block ahead. It was the responsibility of the operator to identify the signal and modify the train speed accordingly. Normally, only one train can occupy a block at any given time. A red signal indicated that another train currently occupied the block. An approaching train was not permitted to enter that block. As trains approached a block occupied by another train, the signals for each block became increasingly restrictive. This system was designed to prevent collisions between trains by slowing the approaching train in time to stop before entering the occupied block.

In addition to the speed limits imposed by the block signal system, there were also civil speed limits. These speed limits were dictated by specific right-of-way characteristics or track geometry. In the current simulation, the civil speed limits varied depending upon whether the block contained a grade crossing. Blocks with grade crossings had lower civil speed limits than blocks without them. In all cases, the prevailing speed limit was the lesser of the block signal limit and the civil speed limit.

Procedures

Training

Due to the complexity of the task and to familiarize the participants with train operations, each participant was given a written tutorial to read prior to their participation in the experiment. The tutorial covered general operating rules that govern railroad operations, how to operate the locomotive simulator, and described the experimental task.

Upon arriving for the experiment, the participant filled out a consent form and completed a multiple-choice test. The test served as a tool to assess their understanding of the material in the tutorial and as a participant selection tool. The test took approximately 10 minutes. Participants scoring correctly on 50 percent or better proceeded to the training phase of the study. All participants achieved this criterion. The experimenter used the test results to identify potential problems with the material that needed to be clarified during the training sessions that followed.

The training session lasted three hours and gave hands-on exposure to the system. During the first hour, the experimenter demonstrated the proper train operation. Next, the experimenter familiarized the participant with the emergency scenarios and the appropriate responses. The remaining two hours were devoted to practice operating the locomotive simulator with and without the failure scenarios to become acquainted with the train control system and its operating modes. During this period, the participant completed a run from station to station using one control mode. During the practice runs, the experimenter was physically present in the cab and monitored how the participants controlled the locomotive. The experimenter recommended proper actions under each control mode. The experimenter also gave the participant suggestions regarding speed compliance. These practice runs lasted about one hour and a half. During the final half-hour of training, the participant completed a run from station to station with the opportunity to experiment with the simulator in any control mode. During this run, the experimenter split his time between the cab and the dispatcher workstation. Additionally, the experimenter suspended the simulation three to four times to familiarize the participants with the interruptions of the simulation that would take place during the experiment to assess situation awareness.

After the training session ended, the experimenter gave the participant a short break and asked whether he or she felt ready to begin the experiment or wanted additional practice operating the train. The participant either requested additional practice trips or proceeded to the experimental trials.

Experimental Task

The participant's task was to control the vehicle speed according to the signal and civil speed limits indicated in each block, look out for potential hazards and respond to them in an appropriate manner.

The participant operated the simulated locomotive from West Station to East Station as shown in Figure 3 and back (one trip), using one particular control mode. At the end of a round trip, the participant was given a brief rest and then began another round trip under a different control mode. Each participant completed three round trips, one for each control mode. Each trip lasted about 45 minutes. Between trips, the participant rested for 10 minutes or longer before proceeding to the next trial. Following completion of the three trips, the participant answered questions regarding their preferences and the workload and stress imposed by the three control modes.

3. RESULTS AND DISCUSSION

Vigilance

Signal detection theory was used to measure the participant’s ability to detect equipment failures. In signal detection theory, detection is a function of two processes: the observer’s perceptual sensitivity and response bias. This theory enables separation of the effects of perceptual sensitivity, in this case, the observer’s ability to detect equipment failures, from response bias. Response bias represents the observer’s tendency to favor one response over another (MacMillan and Creelman, 1991) (i.e., willingness to say “yes” or “no”).

In signal detection theory, events can be categorized in a 2 x 2 matrix showing the relationship between the state of the world and the observer’s response to that state. Figure 4 shows the four possible categories. A hit occurs when a signal is present and the observer reports that the signal is present. A false alarm occurs when a signal is absent and the observer reports that the signal is present. A miss occurs when a signal is present and the observer reports that the signal is absent. A correct rejection occurs when a signal is absent and the observer reports that the signal is absent.

		State of the World	
		Signal	Noise
Observer’s Response	Yes	Hit	False alarm
	No	Miss	Correct rejection

Figure 4. Four Outcomes of Signal Detection Theory

Figure 5 shows how signal detection theory characterizes the relationship between the observer’s responses for two hypothetical distributions. The distribution on the right represents the probability that a signal (i.e., an equipment failure) was present. The distribution on the left represents a probability that noise (i.e., equipment functioned properly) was present. The observer’s ability to detect equipment failure (sensitivity) is reflected by the amount of overlap in the two distributions. Sensitivity increases as the amount of overlap in the two distribution decreases. Response bias is represented by the vertical line showing the response criterion. When the value of the event is to the right of the criterion, the observer will say “yes.” When the value of the event is to the left of the criterion, the observer will say “no.” The response criterion is neutral (zero) when the false alarm rate and miss rate are equal. Moving the criterion to the left increases the likelihood that the observer will say “yes,” while moving the criterion to the right increases the likelihood that the observer will say “no.” Numerically, a positive bias represents the tendency to say no, while a negative bias represents the tendency to say yes.

Sensitivity is typically measured numerically by an index called d prime and response bias is typically measured numerically by an index called beta (β). D prime (d') corresponds to the separation of the mean of two distributions expressed in units of their standard deviations as shown in Figure 5. The response bias, was measured by the ratio of the probability of saying “yes” when the signal is present to the probability of saying “yes” when only noise is present.

For the reader interested in learning more about signal detection theory, refer to books by Green and Swets (1988), Egan (1975), or MacMillan and Creelman (1991).

In this experiment, an alternative measure of sensitivity and response bias was used. D prime and beta cannot be calculated if either hits or false alarms equal zero or 100 percent, as was the case for several conditions. Therefore, nonparametric measures were used to measure sensitivity and response bias. A prime (A') was used (Grier, 1971) to measure sensitivity and B double prime (B") was used to measure response bias. A' measures the area under curve for the measured data point and numerically corresponds to the ratio of hits to false alarms for a given event state. For A prime, values ranged between zero and one. For B double prime, values ranged between minus one and plus one.

To evaluate participants' ability to detect equipment failures, the number of hits and false alarms were recorded. The results for the train equipment failures are summarized in tabular form in Table 3 and graphically in Figure 6. Figure 6 shows the percentage of correctly detected signals (for both motor and bearing failures) in each time block for by control mode. In detecting the train equipment failures, evidence of a statistically significant vigilance decrement is present for all three control modes.[1] For all three conditions, detection of equipment failure declined over time. Detection of the equipment failures under the full supervisory mode was consistently higher than for the other two control modes across all time blocks. Detection performance was the worst in the partial supervisory mode, with the manual control mode falling between the two supervisory control modes. The difference in detection performance between the modes was not statistically significant. However, Lanzilotta (1995) found the same pattern in his study. The lack of statistical significance may be due to the small size of the effect and the small number of data points on which the statistical test was based.

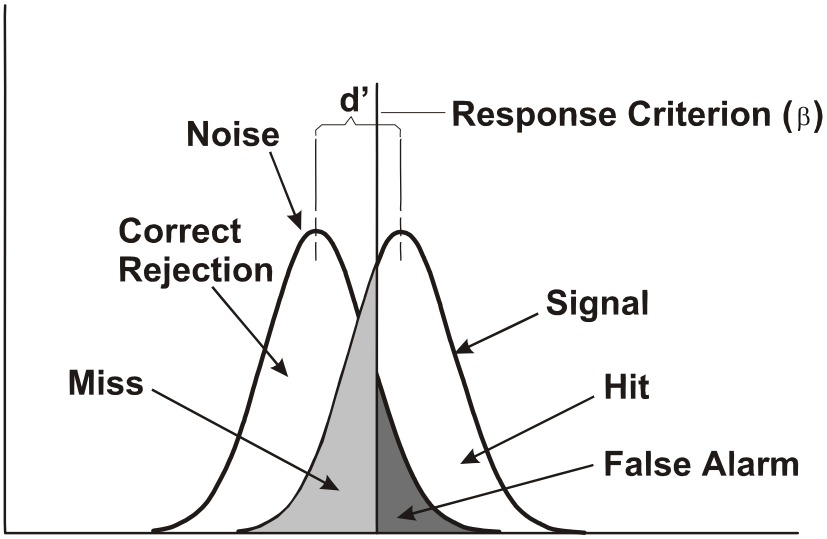


Figure 5. Graphical Depiction of Signal Detection Theory

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[1] The statistical analysis was based upon the Page test. The Page test is a distribution-free test for ordered alternatives based on Friedman rank sums. A discussion of this test is found on page 147 in Hollander and Wolfe, (1973). The test statistic L=41.5 is greater than the critical value for *l* (0.05,3,3)=41 at the 5 percent level of significance.

Table 3. Detection of In-Cab Equipment Failures by Control Mode

	Time block 1	Time block 2	Time block 3	Control Mode Total
		Hits		
Full Supervisory	8	7	7	22
Partial Supervisory	6	6	6	18
Manual	8	7	6	21
Time Block Total	22	20	19	61
		False Alarms		
Full Supervisory	3	3	0	6
Partial Supervisory	2	1	0	3
Manual	0	2	0	2
Time Block Total	5	6	0	11

False alarms decreased over time for the two supervisory control conditions. By contrast, in the manual control condition, false alarms exhibited an inverted u-shaped function, where the number of false alarms went from zero to two and back to zero.

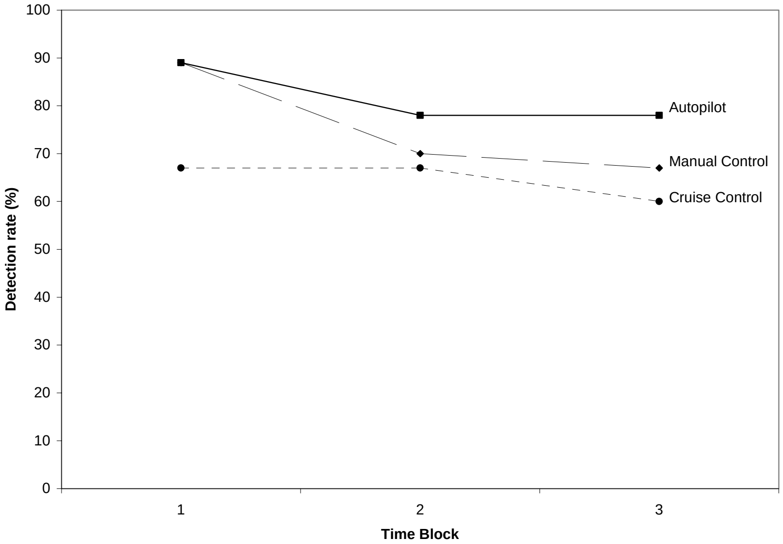

Figure 6. Effects of Train Control Mode on Detection Rate

As shown in Figure 7, the two distributions can also be characterized by the relationship between the probability of hits and false alarms. The vertical axis shows the probability of hits and the horizontal axis shows the probability of false alarms. Sensitivity increases as points on the curve move from the lower right-hand corner to the upper left-hand corner of the chart. Response bias changes from positive to negative as the data points move from the lower left-hand corner to the upper right-hand corner.

When the detection rate and false alarms were examined together, the results show declines in the number of hits and in the number of false alarms over time. This observation suggests that participants changed their response bias over time. For both control mode and time block, sensitivity appeared to change little. Changes in sensitivity are reflected in this chart by differences in the position of the data points along the minor diagonal line.

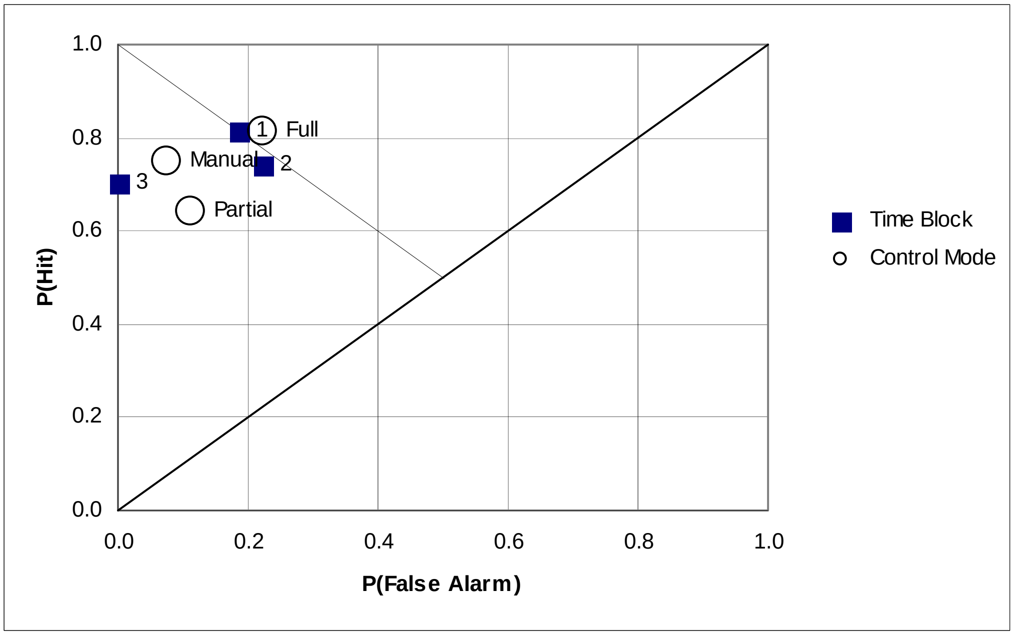

Figure 7. Probability of Hits vs. False Alarms by Train Control Mode and Time (The labels: 1, 2, and 3 represent the time block order)

The impact of control mode and time on detecting equipment failures can be more easily seen by separating the effects of sensitivity and response bias. Figure 8 shows the impact of sensitivity and response bias separately by control mode and time sequence. The top graphs in Figure 8 show the impact of time block and control mode on sensitivity. There is little change in sensitivity across time block or control mode. Sensitivity is relatively high across time and control mode. The differences in sensitivity were not statistically significant.

By contrast, differences were observed for effect of time block and control mode on response bias. The bottom two graphs in Figure 8 show the impact of time block and control mode on response bias. For time block, the response is similar for the first two time blocks. Here the response criterion is neutral with a B" value close to zero. However, for the third time block, the response criterion is highly positive, with a B" at 1.0. These differences were statistically significant (B"=1.0 comparing time block 1 to time block 3, confidence level $_{0.95}$ =0.47; B"=0.96 comparing time block 2 to time block 3, confidence level $_{0.95}$ = 0.45). Thus, participants shifted their response criterion over time so they were highly likely to say, “no, an equipment failure was not present.” This is consistent with past research in the vigilance decrement literature (Getty, Swets, Pickett, and Gonthier, 1995). The observers moved their response criterion (i.e., response bias) as time elapsed so that there were fewer false alarms and fewer hits to reflect the actual probability with which those events were likely to occur.

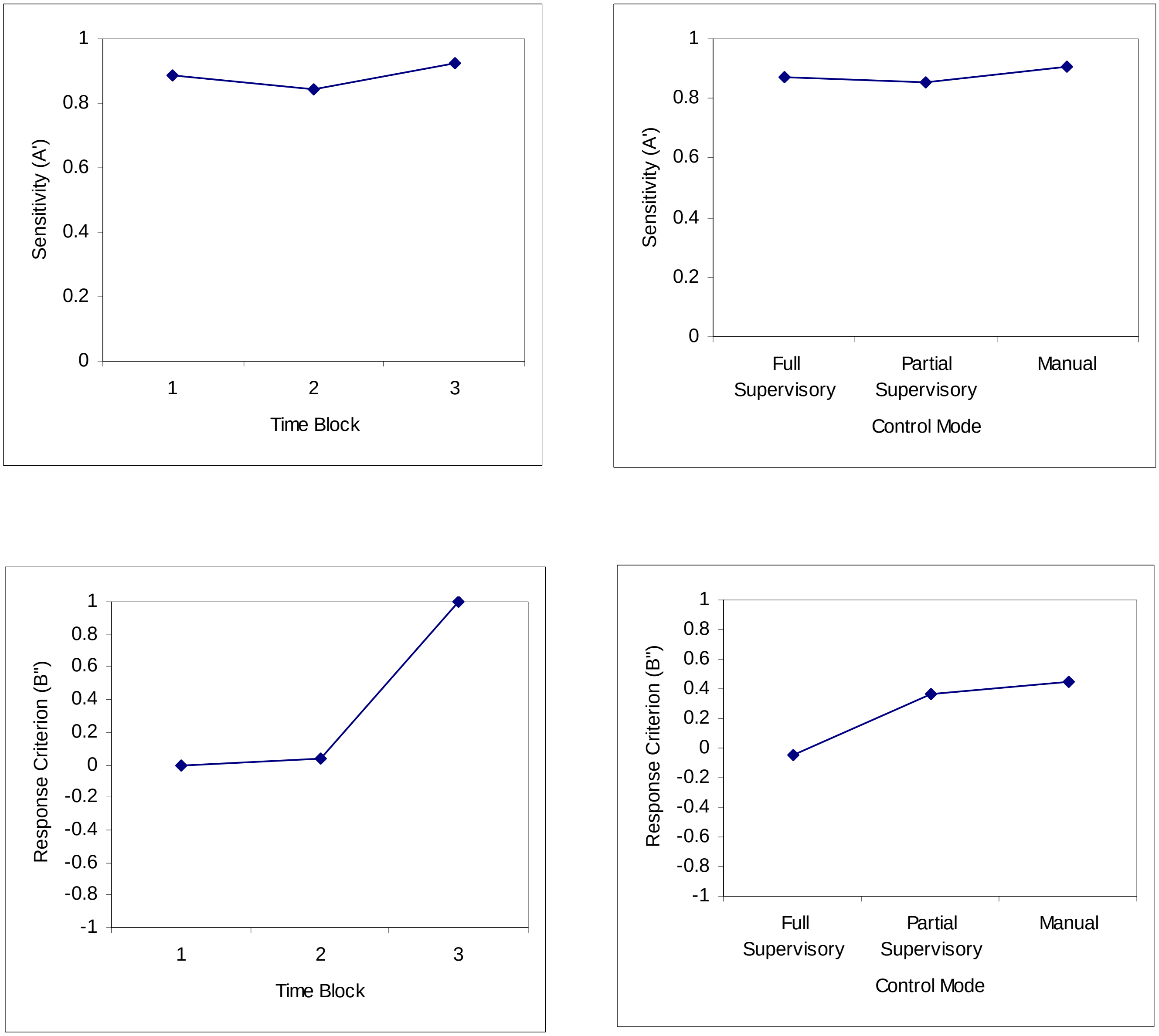

Figure 8. Sensitivity and Response Criterion by Time Block and Control Mode

Response criterion differences were also observed between the three control modes. In the full supervisory mode, participants exhibited slightly negative response criterion, meaning that participants were slightly more likely to say, “yes, an equipment failure occurred” than “no.” By contrast, for both the partial supervisory mode and manual control mode, response criterion was positive. Participants were more likely to say, “No, an equipment failure did not occur” or miss reporting an equipment failure when it did occur. The response bias differences between the full supervisory control mode and the two other modes were not statistically significant at the 95 percent confidence level. The response criterion difference between the full supervisory mode and the manual mode was statistically significant at the 90 percent confidence level. The lack of statistical significance at the 95 percent confidence level may have been due to the small sample size (27 data points per condition). The response criterion differences between the partial control mode and the manual mode were not statistically significant. This behavior suggests that observers would be less likely to miss equipment failures when operating full supervisory train control systems than partial or manual train control systems.

Vigilance monitoring out-the-window between the three control modes differed from the vigilance monitoring associated with the in-cab displays. Figure 9 shows the distance from the obstruction that the vehicle stopped for the three train control modes. Upon detecting an obstruction, all participants made a full service brake application. Next, the participants decided if and when to apply the emergency brakes. In every case but one, participants applied the emergency brakes to avoid a collision.

Participants stopped farthest from the obstruction in the manual control condition followed by the partial supervisory control condition and the full supervisory condition. The differences between the manual mode and both supervisory modes were statistically significant. Using the t-test, the t value for the comparison between manual mode and full supervisory control was $t_{(18)} = 2.037$, $p < 0.05$.[2] For the comparison between manual mode and partial supervisory control, the t value was $t_{(18)} = 1.901$, $p < 0.05$. The difference in stopping distance between the two supervisory control modes was not statistically significant.

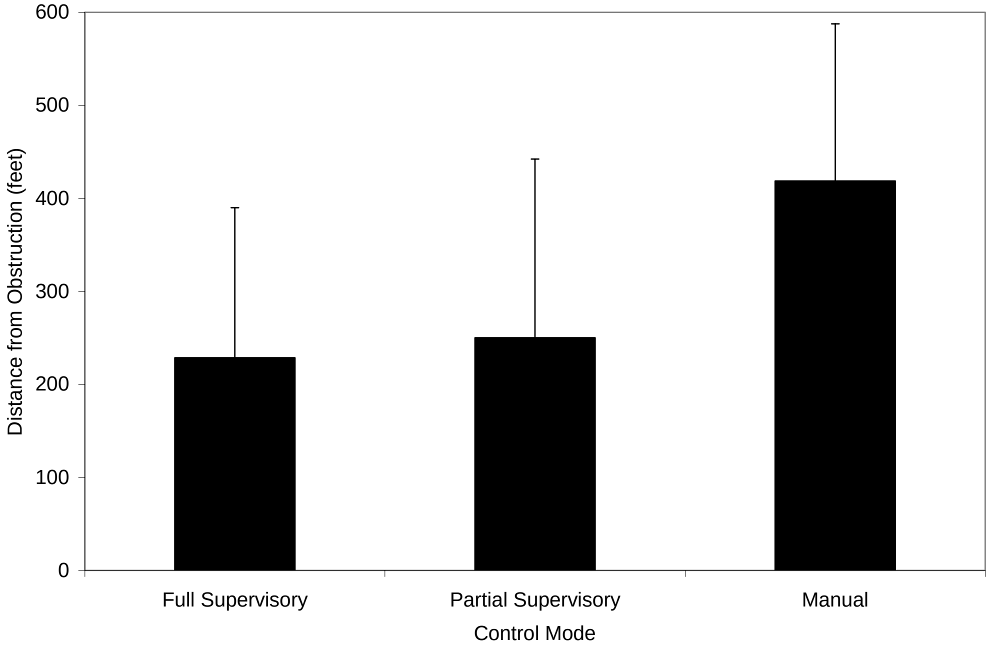

Figure 9. Distance Stopped from an Obstruction

Situation Awareness

During the experimental trials, the simulation was suspended and each participant was asked to report the following items: speed, block number, milepost, brake pressure, bearing temperature and current through the motors. Because the brake pressure was stable over time, there was little deviation in the brake pressure gauges. As a result, there were no reported significant deviations from the actual brake pressure.

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[2] The t-value represents a ratio of systematic errors or unsystematic errors. It measures the difference between two sample means divided by the standard deviation for the sample. The phrase "p < .05" means there are 5 chances in 100 that the observed result was due to chance.

The results for the remaining situation awareness measures are presented in Figure 10, Figure 11, and Figure 12. Figure 10 shows the relationship between train control mode and speed situation awareness. Figure 11 shows the relationship between train control mode and bearing temperature situation awareness. Figure 12 shows the relationship between train control mode and situation awareness with respect to train position and motor status.

For speed awareness, the MAE was lowest in the partial supervisory control mode, followed by the manual control mode and the full supervisory control mode, respectively. A smaller error indicated better situation awareness. These differences were statistically significant.[3]

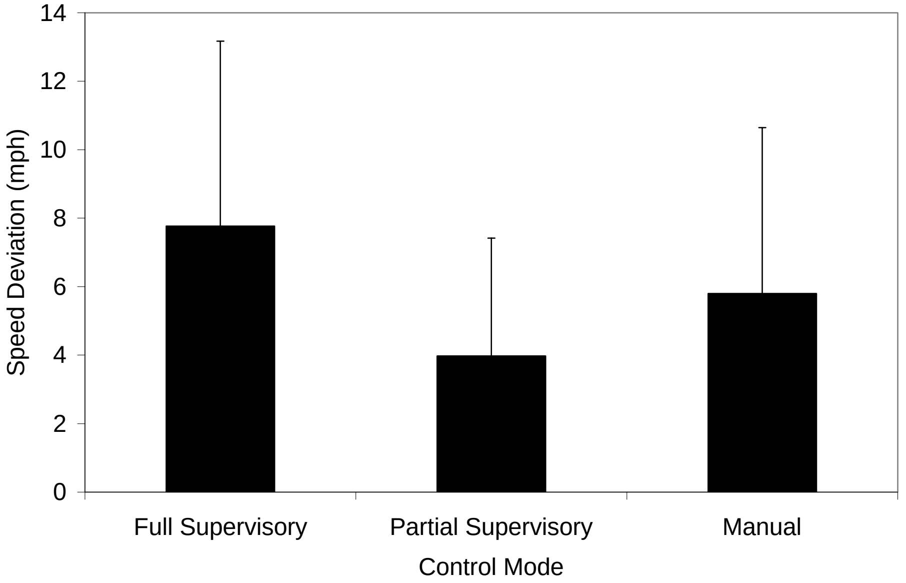

Figure 10. Effects of Train Control Mode on Speed Awareness

Speed awareness was the only measure for which participants performed best in the partial supervisory control mode. However, as Table 4 shows, none of the participants preferred this hybrid control mode. Comments from the participants suggest that the operational implementation of the partial supervisory control mode affected the participants' attention allocation strategies. Many participants complained of difficulty setting the train controls. In the supervisory control mode, participants set the speed using the keyboard function keys while using the control lever to brake or accelerate manually. As a result, they paid more attention to the speedometer, compared to the other control modes to make sure that the train control was achieving the set speed. The difficulty setting the speed control may have contributed to the lower detection rate for in-cab equipment failures compared to the other modes and the higher situation awareness scores for train speed.

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[3] The test statistic L=154 was greater than the critical value for *l* (0.05,3,12)=153, $p<0.05$. The data for this test is presented in Appendix G.

In the full supervisory control mode, participants reported less time monitoring speed than in the other modes, while spending more time attending to other visual displays in the locomotive. To quote one participant:

> "*The full supervisory mode imposed the least workload since I could keep an eye on what was happening, yet I didn't have to worry as much about watching the speed. I had to check to make sure that train control system was following the speed limits, but I didn't actually have to adjust the speed myself. So I could spend my time systematically checking all the information.*"

Participants spent less time monitoring train speed, since the supervisory control system controlled both acceleration and braking and focused more attention elsewhere.

For all other measures of situation awareness (temperature, position, and traction motor awareness), a different pattern emerged from that found with speed awareness. The best performance was observed in the full supervisory control mode, followed by the partial supervisory control mode and manual control mode showing the poorest situation awareness. For temperature, the MAE was lowest for the full supervisory control followed by the partial supervisory control mode and the manual control mode, respectively. This difference was statistically significant.[4] This supports many of the participants' comments that they spent more time monitoring other displays inside the cab compared to the speedometer in the full supervisory control mode.

For train position (as indicated by block number and milepost) and motor status, participants gave the highest percentage of correct answers in the full supervisory control mode.

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[4] The test statistic L=156 was larger than the critical value *l*(0.05,3,12)=153, $p<0.05$. The data for this test is presented in Appendix G.

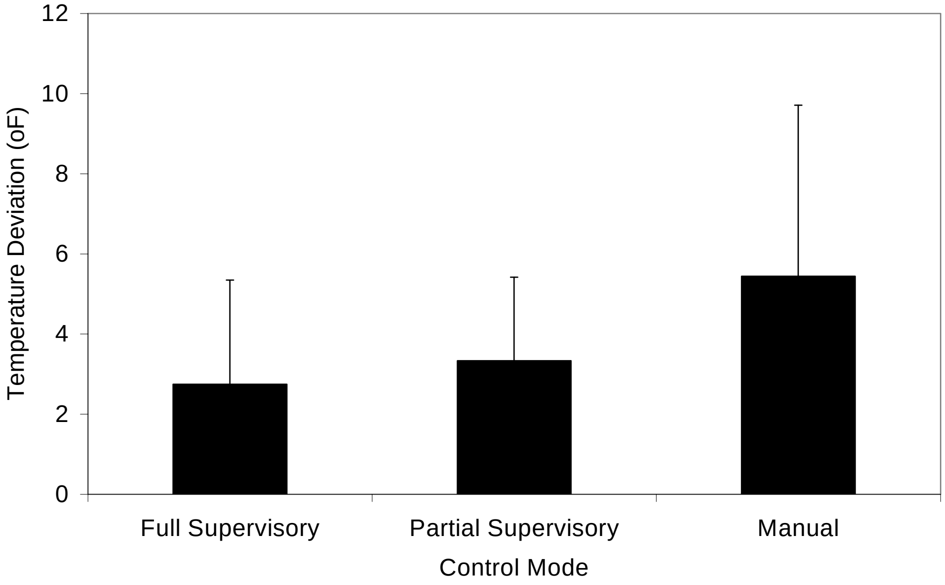

Figure 11. Effects of Train Control Mode on Bearing Temperature Awareness

By contrast, in the manual control mode, block position and motor status awareness were lower than the two supervisory control modes. For milepost, situation awareness was equal between the manual control mode and the partial supervisory control mode.

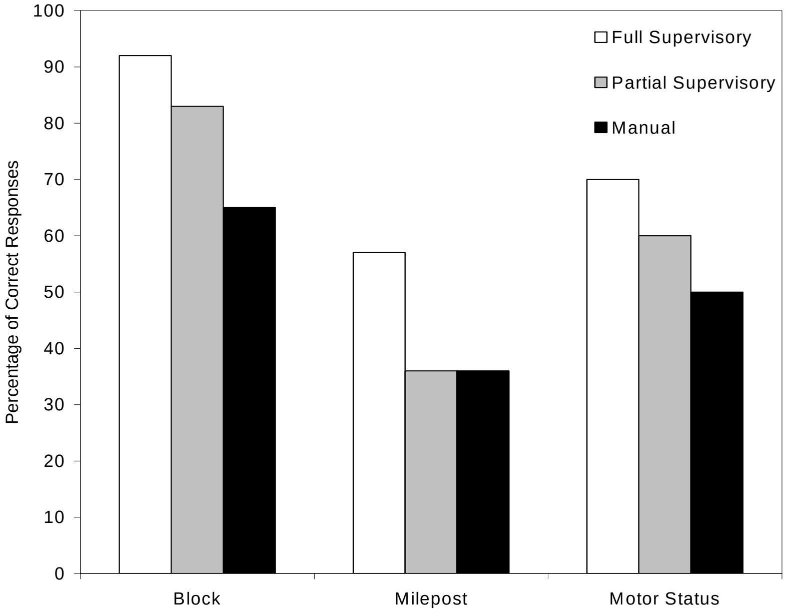

Figure 12. Effects of Train Control Mode on Position and Motor Condition

At the conclusion of the experiment, participants were asked to indicate which control mode created the lowest workload and highest stress level. Participants were also asked to indicate their preferred control mode. The results are shown in Table 4. For workload, participants felt the full supervisory control mode imposed the lowest workload. For the two remaining modes, participants felt the partial supervisory control mode imposed greater workload than the manual control mode. For stress level, participants felt that both supervisory control modes imposed more stress than the manual control mode. Of the two supervisory control modes, full supervisory control was more stressful than the partial supervisory control. A comment by one of the participants described how the control mode affected their stress levels.

> "*I believe that the partial supervisory control and full supervisory control imposed the greatest amount of stress when an obstruction was detected because after setting the speed, I would remove my hands from the control and begin to focus on other potential problems and information that I had to know. When an obstruction occurred, I had to jump from passively driving to actively driving and grab the controls in order to slow down.*"

This comment reflects the challenge required in transitioning between train control modes. Responding to an obstruction on the track in a supervisory mode required the participant to transition from a passive monitor of train speed to an active controller of train speed. Once the obstruction was detected, the participant had a relatively short period to determine what the train was doing and decide how to respond.

While the majority of participants felt full supervisory control imposed the lowest workload, they preferred operating the train manually to full supervisory control. Participants cited a feeling of control over the vehicle along with active engagement in the task, as explanations. No participant chose the partial supervisory control condition as the preferred mode of operation. Participants who preferred the full supervisory control mode cited the lower workload associated with this condition.

Table 4. Participant Preferences for Train Control Mode from Exit Interview

	Train Control Mode		
	Full	Partial	Manual
Lowest Workload (%)	83	0	17
Most Stressful (%)	75	25	0
Preference (%)	33	0	67

Summary

Overall, supervisory train control systems improved situation awareness and vigilance performance compared to manual operation. However, differences in the way the supervisory control systems operated contributed to differences in attention allocation. These differences were greatest for unexpected events such as equipment failures and obstructions at highway-railroad grade crossings. A signal detection analysis indicated that the supervisory control system influenced the observer's response strategies, but not perceptual sensitivity in detecting equipment failures. There were no differences in sensitivity between the three control modes. By contrast, participants in the partial supervisory control condition exhibited a tendency similar to the manual control condition, to say in-cab failures did not occur, while the participants in the full supervisory control condition exhibited a slight preference to say an in-cab failure did occur.

In the full supervisory control system, the system adjusted speed based upon information from the in-cab signal system. If the speed limit changed, the train control system made the adjustment without assistance from the operator. This assistance enabled the participant to attend to other tasks. Compared to manual operation, participants showed greater situation awareness for non-speed-related events such as bearing temperature, traction motor status, milepost, and block location.

However, participants showed greater difficulty with speed-related tasks compared to the manual control mode. Participants exhibited the poorest situation awareness for speed in the full supervisory control condition. The implications of this behavior can be seen in obstruction detection. Participants took longest to stop when an obstruction was present in full supervisory control. Obstruction detection performance in the partial supervisory control mode was similar to the full supervisory control mode. While the participant relied upon the system for routine speed control decisions, the participant had to intervene when an event outside the scope of the train control system (i.e., an obstruction on the track) occurred. The participant responded by deactivating the supervisory control system and taking over active control of the train. Although the participant may have detected the obstruction as early or earlier than in the manual mode, making a decision about the proper amount of braking was delayed while speed information was gathered. Compared to the manual control condition, more time was required to understand the situation. Where supervisory control systems are provided to enable train control operations that could not take place safely without them (i.e., high-speed operation), the likelihood for the locomotive engineer to successfully intervene when the train control system encounters an event it is not prepared to handle, will decrease. This finding is consistent with Wickens and Kessel's (1979) research showing that observers were better at detecting a sudden change in system state when manually controlling the system than when monitoring the system.

The challenge for developers of train control systems is learning how to design the interface so the operator remains actively engaged in safety critical tasks. Attention to activities directly related to train movement is critical to safe operation. However, using technology in a way that degrades the direct involvement of the operator with the system can make it more difficult to detect and recover from errors (Huey and Wickens, 1993). This degradation in safety critical aspects of their performance was also reflected in the participant's response to questions about workload and stress. Participants rated the full supervisory condition as having the lowest workload, but the highest stress. These comments indicated their discomfort with not being actively engaged in a safety critical aspect of the train operation.

The partial supervisory control mode method for assisting with speed control showed some similarity with the full supervisory control system in its impact on attention allocation. Like the supervisory control mode, this control mode resulted in participants monitoring events such as bearing temperature, traction motor status, and block location better than in manual mode. It also showed an important difference from the full supervisory control mode. Unlike the full supervisory control mode, performance in the speed awareness was better in the partial supervisory control mode than in the manual mode.

The participants attributed need to allocate more attention resources to speed to their difficulty in setting the desired speed. The partial supervisory control system in this study increased perceived workload compared to the manual control mode and focused the participant's attention more narrowly than the full supervisory control mode. Participants attended more closely to the speed display compared to the full supervisory control mode. This design may have prevented participants from allocating their attention as broadly as in the full supervisory mode and contributed to the vigilance decrement for unexpected events like equipment failures. Additionally, greater speed awareness failed to translate into better performance when it came time to take over active control of the train when the train control system was not equipped to handle the situation. Again, participants took longer to stop in response to a track obstruction compared to manual control.

The current study examined equipment failures that were unrelated to the supervisory control system, itself. However, the problem of reliance may be compounded if the supervisory control system, itself fails without adequate warning to the operator. Stanton and Young (1998) discuss three studies examining the use of adaptive cruise control in motor vehicles. These studies evaluated the ability of motorists to detect and respond to adaptive cruise control failures. When the adaptive cruise control failed, drivers collided with moving or stationary vehicles more frequently compared to manual operation. Expectations by the driver that the cruise control technology would deal with this situation may have contributed to this detection failure. In other words, the driver trusted the system based upon experience showing reliable behavior. The more reliable the control system appears to be, the more the operator may depend on the control system. For highly reliable control systems, failures may be very difficult to detect without an adequate warning.

The results of this experiment indicate that supervisory control systems can impact operator performance in non-intuitive ways. The two types of supervisory control in this study both controlled speed, but they affected human performance differently. The complex relationship between supervisory control systems and human performance, suggests the need for human-in-the-loop testing to evaluate new train control systems for their impact on human performance before they are implemented in revenue service. Human-in-the-loop testing of supervisory control systems can identify the likely human errors. Through an iterative design process and training, some of these errors may be eliminated. For errors that cannot be eliminated, designers can facilitate recovery by making actions reversible and creating warnings to alert the operator when they occur.

APPENDIX A. BONUS AND PENALTY POINT SYSTEM

An incentive system was created to encourage participants to attend to the schedule and failure events. For each participant, the points were converted to money at the rate of one dollar for every 1000 points. A participant with a negative score would receive no money beyond what all participants were paid for participating in the study. Participants were paid after completing the experiment. Bonus or penalty points were awarded for the following behaviors:

- Schedule accuracy,
- Response to motor failure,
- Response to bearing failure,
- Response to brake failures,
- Application of emergency brake,
- Response to a grade crossing obstruction, and
- Answers to situation awareness questions.

Figure A-1 shows the number of points awarded to the participant for schedule accuracy. Completing the trip in less then 45 minutes results the participant receiving (bonus) points. Completing the trip in more than 45 minutes results in the participant losing points (penalty). Figure A-2 summarizes the incentive system applied to motor and bearing failures.

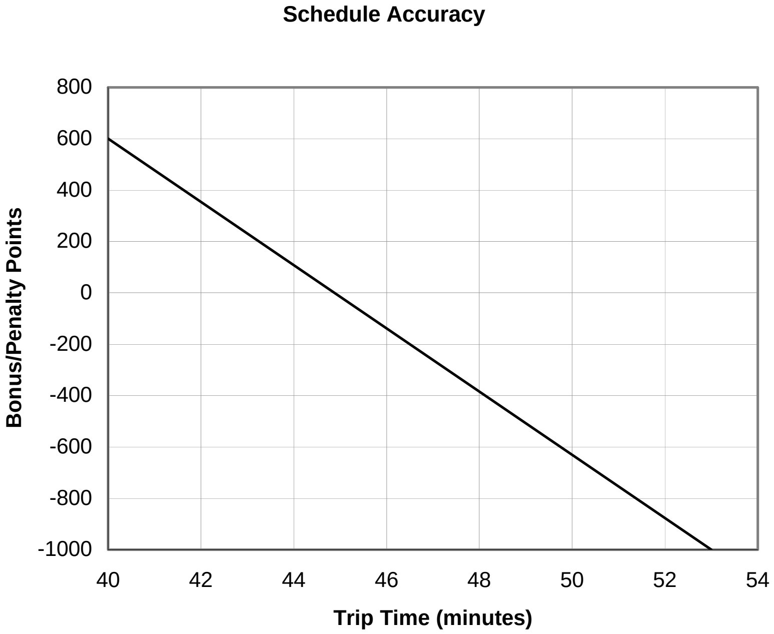

Figure A-1. Schedule Accuracy Bonus/Penalty Points

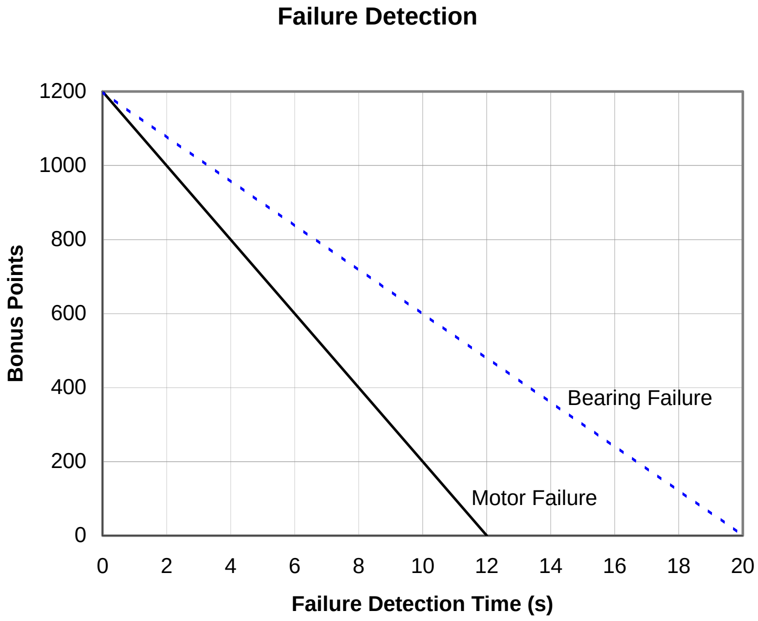

Figure A-2. Emergency Response Time Bonus Points

When a brake failure occurred, participants were given 800 points for observing and resetting the brakes. Penalties were given for application of the emergency brakes. Table A-1 shows the penalty schedule for brake applications under different circumstances. In fact, penalties regarding inappropriate application of the emergency brakes will result as shown in Table A-1.

Table A-1. Penalties Resulting from Application of the Emergency Brakes

Emergency Stop braking	Penalties
Triggered by ATP:	-2000
Triggered by the Alerter:	-2000
Triggered by the operator - collision avoidance:	-100
Triggered by the operator - no reason:	-300

For obstructions at grade crossings, bonus and penalty points were assessed according to the schedule shown in Table A-2.

Table A-2. Obstruction Hazards Bonus/Penalty Scheme

Obstruction Outcome	Bonus/Penalty
Collision avoidance:	+1000
Collision Speed: >=55.9 mph	-1000
Collision 43.5 mph <= Speed <= 90 mph	-800
Collision 24.8 mph <= Speed <= 43.5 mph	-600
Collision 6.2 mph <= Speed <= 24.8 mph	-450
Collision Speed<= 6.2 mph	-250

Participants were awarded 1000 bonus points for each correct answer to the situation awareness questions. Participants received no points if the answer was incorrect.

APPENDIX B. NEW FEATURES OF HIGH-SPEED TRAIN SIMULATOR

For the purposes of the present research, several new features were added to the train simulator. These features are described below:

- <u>Suspend/resume capabilities in the train simulator</u>. This feature is designed for gathering situation awareness data. This feature enables the experimenter to suspend the simulation and ask questions relevant to the state of the vehicle. Two versions were designed and implemented: in the version used in the experiment, the out-the-window view and dashboard displays were blanked. Only the communications window remains active so that the participant can communicate with the experimenter. In the other version, both screens are just frozen but not blanked. One can invoke the later version by using the `-noblank` flag in the command line argument when running the train simulation. In any case, provision has been made for the simulator to record everything pertaining to the state of the train as well as the participant's response. Additional provision was made to reset the simulation clock.
- <u>Enable the experimenter to activate/deactivate Automatic Train Protection from the CTC screen</u>. This option can be invoked using the `-atp` flag when running the CTC simulation.
- <u>A new version of the autopilot</u>. In the previous version of the simulator, the full supervisory control mode (autopilot), once invoked, would control the speed of the train adhering only to civil speed limits. When a signal was present the autopilot would fail to recognize it and the vehicle operator needed to assume manual control to adjust the vehicle speed. In the current version, the full supervisory control mode would recognize civil and signal speed limits simultaneously and adhere to the lesser of the two, thus replicating existing train supervisory control mode such as the one used in the German ICE high speed train. Under normal conditions, the operator need not interfere with speed control of the train but only monitor that the full supervisory control mode adheres to the speed limits of each block. This version of the full supervisory control mode can be realized using the `-full_auto` flag in the command line argument when running the train simulation.
- <u>A bearing failure</u>. In this scenario, the temperature of a faulty bearing rises due to increased friction in its rollers. The rate at which the temperature goes up under failure conditions is higher than under normal conditions.
- <u>A failure reset mode to gather vigilance data</u>. In older versions of the simulator, once the failures were set they remained active until the participant noticed them. In the current version, the software can reset the failures according to the time that elapsed or the distance that the train traveled since the onset of the failure, in the event that the participant has not been able to spot and reset them in time. This mode was selected using the `-fail_reset` option in the command line argument of the main simulation. The programmer must enter the keywords `time` followed by the time in milliseconds the failure will remain active, or `distance` followed by the distance that the vehicle will travel before the failure is reset in the failure input file.

APPENDIX C. LOCATION OF FAILURE EVENTS

The positions on the track at which failure events were set to occur are shown below.

Distance from station (miles)	Direction	Time block
Motor Failure		
8.2	Eastbound	1st
25.2	Eastbound	2nd
19.0	Westbound	3rd
Bearing failure		
20.7	Eastbound	1st
1.9	Westbound	2nd
16.2	Westbound	3rd
Grading crossing		
0.9	Eastbound	-
13.3	Eastbound	-
14.1	Eastbound	-
14.0	Westbound	-
16.5	Westbound	-
29.9	Westbound	-

APPENDIX D. VIGILANCE DETECTION TASK DATA

Subject 1

Control mode	Task	Response	Reaction
Full Supervisory	m1	hit	8.205 s
	b3	miss	-
	o6	No collision	Stop 299.27 ft
Partial Supervisory	m2	hit	2.28 s
	b3	hit	5.595 s
	o5	No collision	Stop 262.92 ft
Manual	b1	hit	8.22 s
	b2	hit	15 s
	m3	hit	1.981 s
	o4	No collision	Stop 607.18 ft

Subject 2

Control mode	Task	Response	Reaction
Full Supervisory	b1	hit	7.206 s
	b2	hit	13.194 s
	m3	hit	3
	o1	No collision	Stop 217.74 ft
Partial Supervisory	b2	miss	-
	m3	hit	3.1
	o3	No collision	Stop 292.68 ft
Manual	m1	hit	9.48
	b3	miss	-
	o6	No collision	Stop 261.15

Subject 3

Control mode	Task	Response	Reaction
Full Supervisory	b2	hit	9.86 s
	m3	hit	8.7 s
	o3	No collision	Stop 459.31 ft
Partial Supervisory	m1	hit	5.45 s
	b3	hit	13.1 s
	o6	No collision	Stop 86.77 ft
Manual	b1	hit	12.85 s
	m2	miss	-
	b3	hit	15.7 s
	o1	No collision	645.56 ft

Legend

b = bearing failure
m = motor failure
o = obstruction

s = seconds
ft = feet

Subject 4			
Control mode	Task	Response	Reaction
Full Supervisory	b2	miss	-
	m3	hit	7.38 s
	o3	No collision	Stop 365.81 ft
Partial Supervisory	m1	hit	2.945 s
	m3	miss	-
	o6	No collision	Stop 249.90 ft
Manual	b1	hit	6.364 s
	m2	miss	-
	b3	miss	-

Subject 5			
Control mode	Task	Response	Reaction
Full Supervisory	b1	hit	12.98 s
	m2	hit	3.54 s
	o5	No collision	Stop 14.43 ft
Partial Supervisory	m1	miss	-
	m3	hit	3.06 s
	o6	No collision	Stop 12.17 ft
Manual	b1	hit	3.46 s
	m2	hit	3.66 s
	b3	hit	17.6 s
	04	No collision	Stop 310.95 ft

Subject 6			
Control mode	Task	Response	Reaction
Full Supervisory	b1	hit	15.59 s
	m2	miss	-
	b3	hit	15.74
	o5	No collision	Stop 123.58 ft
Partial Supervisory	m2	hit	7.8 s
	b1	miss	-
	o6	No collision	Stop 55.77 ft
Manual	b1	hit	8.154 s
	m2	hit	6.24 s
	o1	No collision	Stop 229.95 ft

Legend

b = bearing failure
m = motor failure
o = obstruction

s = seconds
ft = feet

Subject 7

Control mode	Task	Response	Reaction
Full Supervisory	b1	hit	16.06 s
	m2	hit	3.13 s
	o5	No collision	Stop 89.17 ft
Partial Supervisory	m1	hit	2.465 s
	b2	hit	17.132 s
	o6	No collision	292.61 ft
Manual	b2	hit	16.87 s
	b3	hit	19.68 s
	o1	No collision	Stop 283.46 ft

Subject 8

Control mode	Task	Response	Reaction
Full Supervisory	m1	miss	-
	b2	hit	15.6 s
	o5	No collision	Stop 185.30 ft
Partial Supervisory	m1	miss	-
	b2	miss	-
	m3	hit	3.48 s
	o6	No collision	171.1 m
Manual	m1	hit	10.8 s
	m3	hit	7.2 s
	o1	No collision	Stop 225.81 ft

Subject 9

Control mode	Task	Response	Reaction
Full Supervisory	m1	hit	3.545 s
	b3	hit	17.405 s
	o6	collision	-
Partial Supervisory	m2	hit	6.481 s
	b3	miss	-
	o5	No collision	Stop 518.37 ft
Manual	m1	miss	-
	b2	miss	-
	m3	hit	s
	o1	No collision	Stop 435.23 ft

Legend

b = bearing failure
m = motor failure
o = obstruction

s = seconds
ft = feet

Subject 10

Control mode	Task	Response	Reaction
Full Supervisory	b2	hit	16.2 s
	m3	hit	3 s
Partial Supervisory	b1	hit	7.32 s
	m2	miss	-
	b3	miss	-
	o5	collision	-
Manual	m1	hit	3.125 s
	b2	hit	13.8 s
	o6	No collision	Stop 163.66 m

Subject 11

Control mode	Task	Response	Reaction
Full Supervisory	m1	hit	3.125 s
	m3	miss	-
	o5	No collision	Stop 95.75 m
Partial Supervisory	b1	hit	8.288 s
	m2	hit	4.51 s
	b3	hit	11.04 s
	o2	collision	Stop 62.79 m
Manual	m2	hit	3.361 s
	m3	miss	-
	o4	No collision	Stop 125.44 m

Subject 12

Control mode	Task	Response	Reaction
Full Supervisory	b1	hit	12.91 s
	m2	hit	4.4 s
	b3	hit	15.34 s
	o4	No collision	Stop 134.88 m
Partial Supervisory	m1	hit	2.9 s
	b2	hit	7.261 s
	m3	miss	-
	o5	No collision	Stop at 142.92 m
Manual	b2	hit	8.4 s
	o3	No collision	Stop 199.39 m

Legend

b = bearing failure
m = motor failure
o = obstruction

s = seconds
ft = feet

APPENDIX E. DATA FOR PAGE TEST

Differences between the participants' speed estimates and the actual speed were used to compute the Mean Absolute Error (*MAE*) in the speed category. The numbers in parentheses indicate the ranks as required by the test. Details on how the ranks are used by the test can be found in Hollander and Wolfe (1973), page 147.

Participant	Speed Deviation (mph) by Control Modes		
	Full Supervisory	Partial Supervisory	Manual
1	1.9 (3)	1.1 (1)	1.4 (2)
2	17.4 (3)	2.9 (1)	16.8 (2)
3	13.0 (3)	3.1 (2)	2.8 (1)
4	14.9 (3)	4.1 (1)	5.6 (2)
5	1.2 (1)	10.6 (3)	6.2 (2)
6	5.3 (3)	1.4 (2)	0.2 (1)
7	3.1 (2)	1.2 (1)	4.7 (3)
8	10.6 (3)	1 (1)	1.3 (2)
9	6.2 (1)	9.3 (3)	8.7 (2)
10	9.3 (3)	5.5 (1)	9.3 (2)
11	6.0 (3)	0.4 (1)	2.3 (2)
12	3.2 (1)	6.8 (2)	8.7 (3)

Differences between the participants' temperature estimates and the actual temperature were used to compute the *MAE* in the temperature category. The numbers in parentheses indicate the ranks as required by the test. Details on how the ranks are used by the test can be found in Hollander and Wolfe (1973), page 147.

Participant	Temperature Deviation (^{o}F) by Control Mode		
	Full Supervisory	Partial Supervisory	Manual
1	39 (1)	44 (2)	52 (3)
2	39 (1)	40 (2)	55 (3)
3	37 (1)	38 (2)	50 (3)
4	40 (3)	34 (1)	38 (2)
5	33 (1)	35 (2)	40 (3)
6	37 (1)	37 (2)	37 (3)
7	33 (2)	35 (3)	32 (1)
8	50 (3)	37 (1)	44 (2)
9	33 (1)	37 (3)	35 (2)
10	34 (2)	33 (1)	34 (3)
11	35 (1)	41 (2)	42 (3)
12	35 (1)	45 (3)	38 (2)

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