U.S. Department
of Transportation

**Federal Railroad
Administration**

Technology Implications of a Cognitive Task Analysis for Locomotive Engineers

**Office of Research
and Development
Washington, DC 20590**

Human Factors in Railroad Operations

DOT/FRA/ORD-09/03

Final Report
January 2009

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REPORT DOCUMENTATION PAGE	Form Approved OMB No. 0704-0188

1. AGENCY USE ONLY (*LEAVE BLANK*)	2. REPORT DATE September 2007	3. REPORT TYPE AND DATES COVERED Final Report October 2003- December 2006

4. TITLE AND SUBTITLE Technology Implications of a Cognitive Task Analysis for Locomotive Engineers	5. FUNDING NUMBERS EB101/RR04
6. AUTHOR(S) Emilie Roth and Jordan Multer	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) U.S. Department of Transportation Research and Innovative Technology Administration John A. Volpe National Transportation Systems Center Cambridge, MA. 02142-1093	8. PERFORMING ORGANIZATION DOT-VNTSC-FRA-08-06
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) U.S. Department of Transportation Federal Railroad Administration Office of Research and Development Washington, DC. 20590	10. SPONSORING/MONITORING AGENCY REPORT NUMBER DOT/FRA/ORD-09/03
11. SUPPLEMENTARY NOTES COTR: Dr. Thomas Raslear, Federal Railroad Administration	
12a. DISTRIBUTION/AVAILABILITY STATEMENT This document is available to the public through the National Technical Information Service, Springfield, VA 22161	12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

This report documents the results of a cognitive task analysis (CTA) that examined the cognitive demands and activities of locomotive engineers in today's environment and the changes in cognitive demands and activities that are likely to arise with the introduction of new train control technologies. The CTA combined structured interviews with experienced locomotive engineers, conductors, and trainers and direct observations made during head-end rides. Data were collected at seven sites, that included both passenger and freight railroads, including five locations where railroads were field testing advanced train control technologies. The results pointed to major cognitive challenges involved in operating a train, including the need for sustained monitoring and attention; maintaining an accurate situation model of the immediate environment (including the location, activities and intentions of other agents in the vicinity such as other trains and roadway workers); anticipating and taking action in preparation for upcoming situations; and planning and decision making, particularly in response to unanticipated conditions (e.g., person or object obstructing the track). Introduction of new train control technology reduces some cognitive demands while creating new ones. The report discusses implication of the results for design of in-cab displays and development of training, particularly for positive train control systems.

14. SUBJECT TERMS Cognitive task analysis, communications, decision-making, human factors, locomotive engineer, positive train control (PTC), railroad operations, train handling, teamwork	15. NUMBER OF PAGES 56 16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	Unclassified

METRIC/ENGLISH CONVERSION FACTORS

ENGLISH TO METRIC

LENGTH (APPROXIMATE)

1 inch (in)	=	2.5 centimeters (cm)
1 foot (ft)	=	30 centimeters (cm)
1 yard (yd)	=	0.9 meter (m)
1 mile (mi)	=	1.6 kilometers (km)

AREA (APPROXIMATE)

1 square inch (sq in, in^2)	=	6.5 square centimeters (cm^2)
1 square foot (sq ft, ft^2)	=	0.09 square meter (m^2)
1 square yard (sq yd, yd^2)	=	0.8 square meter (m^2)
1 square mile (sq mi, mi^2)	=	2.6 square kilometers (km^2)
1 acre = 0.4 hectare (he)	=	4,000 square meters (m^2)

MASS - WEIGHT (APPROXIMATE)

1 ounce (oz)	=	28 grams (gm)
1 pound (lb)	=	0.45 kilogram (kg)
1 short ton = 2,000 pounds (lb)	=	0.9 tonne (t)

VOLUME (APPROXIMATE)

1 teaspoon (tsp)	=	5 milliliters (ml)
1 tablespoon (tbsp)	=	15 milliliters (ml)
1 fluid ounce (fl oz)	=	30 milliliters (ml)
1 cup (c)	=	0.24 liter (l)
1 pint (pt)	=	0.47 liter (l)
1 quart (qt)	=	0.96 liter (l)
1 gallon (gal)	=	3.8 liters (l)
1 cubic foot (cu ft, ft^3)	=	0.03 cubic meter (m^3)
1 cubic yard (cu yd, yd^3)	=	0.76 cubic meter (m^3)

TEMPERATURE (EXACT)

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METRIC TO ENGLISH

LENGTH (APPROXIMATE)

1 millimeter (mm)	=	0.04 inch (in)
1 centimeter (cm)	=	0.4 inch (in)
1 meter (m)	=	3.3 feet (ft)
1 meter (m)	=	1.1 yards (yd)
1 kilometer (km)	=	0.6 mile (mi)

AREA (APPROXIMATE)

1 square centimeter (cm^2)	=	0.16 square inch (sq in, in^2)
1 square meter (m^2)	=	1.2 square yards (sq yd, yd^2)
1 square kilometer (km^2)	=	0.4 square mile (sq mi, mi^2)
10,000 square meters (m^2)	=	1 hectare (ha) = 2.5 acres

MASS - WEIGHT (APPROXIMATE)

1 gram (gm)	=	0.036 ounce (oz)
1 kilogram (kg)	=	2.2 pounds (lb)
1 tonne (t)	=	1,000 kilograms (kg)
	=	1.1 short tons

VOLUME (APPROXIMATE)

1 milliliter (ml)	=	0.03 fluid ounce (fl oz)
1 liter (l)	=	2.1 pints (pt)
1 liter (l)	=	1.06 quarts (qt)
1 liter (l)	=	0.26 gallon (gal)
1 cubic meter (m^3)	=	36 cubic feet (cu ft, ft^3)
1 cubic meter (m^3)	=	1.3 cubic yards (cu yd, yd^3)

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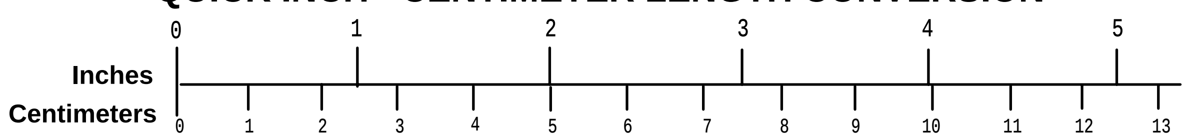
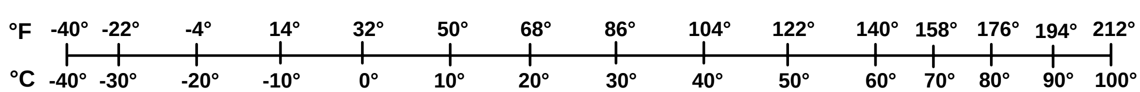
QUICK INCH - CENTIMETER LENGTH CONVERSION



QUICK FAHRENHEIT - CELSIUS TEMPERATURE CONVERSION



For more exact and or other conversion factors, see NIST Miscellaneous Publication 286, Units of Weights and Measures. Price $2.50 SD Catalog No. C13 10286

Updated 6/17/98

Acknowledgements

The Federal Railroad Administration's (FRA) Office of Research and Development funded this research effort. We would like to thank FRA's Office of Research and Development for the opportunity to perform and document cognitive analyses of train crew operations. We would like to thank Dr. Thomas Raslear, Senior Human Factors Program Manager, for his support and guidance.

We would like to acknowledge a number of individuals who generously provided their time and support. We would like to thank Don Scott, General Manager Operations, Standards & Compliance & System General Road Foreman, National Railroad Passenger Corporation, for providing us the opportunity to interview Locomotive Engineers and training instructors at the Amtrak Training Center in Wilmington, DE; Alan Polivka, Communications & Train Control Technologies General Manager North American Joint Positive Train Control (NAJPTC) Project Transportation Technology Center, Inc.; and Dan Steinhoff, Union Pacific, for providing us the opportunity to ride a test train during one of the early NAJPTC field tests that was conducted in Bloomington, IL, on October 29, 2002, and sharing their insights. We would also like to thank Bob Kollmar, Amtrak, for providing us the opportunity to learn about the incremental train control system (ITCS) and the lessons learned from the system's development and implementation. We are grateful to Bob for arranging for us to get a head-end ride on an ITCS-equipped train and making available ITCS locomotive engineers to be interviewed in Chicago, IL, and Niles, MI. We would also like to thank John Vogler, New Jersey Transit, who provided us the opportunity to interview Advanced Speed Enforcement System (ASES) locomotive engineers.

We would also like to acknowledge the national and local labor representatives of the Brotherhood of Locomotive Engineers (BLE) and the United Transportation Union (UTU). We especially want to thank Bob Harvey, Tom Pontolillo, and James Stem for communicating with their respective memberships in support of this project. The visible support of labor for this effort was important for reassuring the individuals that we interviewed that both labor and management was interested in their input and supported this work.

Finally, we want to express our special thanks to all of the locomotive engineers and conductors who agreed to participate in the interviews and focus groups. Their candid comments and insights were critical to the success of this project.

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Executive Summary

Railroad operations in the United States are undergoing rapid changes. This includes introduction of faster trains, increased demands on track usage, and new train control technologies such as positive train control (PTC). As part of its efforts to investigate the safety implications of operational changes and emerging technologies, the Federal Railroad Administration's (FRA) Office of Research and Development sponsored a series of Cognitive Task Analyses (CTA) to examine the cognitive and collaborative demands associated with different railroad operations positions. The first CTA focused on railroad dispatchers (Roth, Malsch, & Multer, 2001). A second CTA addressed roadway worker activities (Roth and Multer, in preparation). The present report documents the results of a CTA that was conducted to examine the cognitive and collaborative demands and activities of locomotive engineers.

An important aim of CTA was to identify cognitive activities that could be supported more effectively through the introduction of advanced technologies such as PTC technologies that are currently being developed by the railroad industry and evaluated as a part of FRA research and development efforts. A second, related, aim was to anticipate new sources of cognitive demands and complexities that the new technologies might pose. Although PTC technologies have the potential to improve safety and efficiency of railroad operations, they also have the potential to create new failure modes and impose new cognitive demands on locomotive engineers who need to monitor PTC displays and provide inputs to the system. Part of the objective of CTA was to understand these potential new performance demands.

While the report focuses primarily on the activities of the locomotive engineer, we recognize that train crews operating in the United States generally include two individuals, typically a locomotive engineer and a conductor. The report includes discussion of the interaction between the two individuals and how they work jointly to operate the train in a safe and efficient manner.

The CTA was based on an extensive series of interviews and observations that were made at 7 sites between February 2000 and September 2005. These sites included both intercity passenger operations, commuter operations and freight operations. Five of the sites were at locations where railroads were in the process of field testing advanced train control technologies. PTC systems we examined included communications-based train management (CBTM), advanced speed enforcement system (ASES), incremental train control system (ITCS), electronic train management system (ETMS), and North American Joint Positive Train Control (NAJPTC).

The CTA identified the major cognitive functions that underlie locomotive engineer performance and the factors that contribute to cognitive challenges. Important cognitive functions include the need to maintain broad situation awareness and develop an accurate current situation model of the immediate environment (including the location, activities and intentions of other agents in the vicinity such as other trains and roadway workers); the need to generate expectations and think ahead so as to know where to focus attention, prepare for anticipated actions, as well as plan for contingencies; the need to actively engage in sustained visual and auditory monitoring, including monitoring radio communication; the need to manage multiple demands on attention; the need to prioritize and manage multiple goals; and the need for rapid decision-making in response to unanticipated conditions (e.g., a person or object obstructing the track). Complicating factors/challenges include poor visibility, missing and obscured signs, dynamically

changing conditions (e.g., temporary speed restrictions and work zones), multiple demands on attention, and delays and reroutes that interfere with the ability to anticipate and prepare for upcoming events.

Experienced locomotive engineers have developed knowledge and skills that allow them to operate safely and efficiently. These include strategies for obtaining the information required to form an accurate model of the current situation and maintain broad situation awareness (e.g., by listening in to radio communications directed at others). This allows them to anticipate upcoming events and prepare for contingencies. They have also developed train handling strategies that allow them to rapidly assess and adapt to locomotive and consist characteristics, the terrain, and the automated train control technologies. These include strategies for operating the train efficiently and maintaining the train schedule as well as strategies for detecting and responding to emergency situations (e.g., a broken rail; switch in wrong position; or a person or object obstructing the track).

The interviews and observations that we conducted at sites where new train control technologies were being introduced revealed that while these new technologies reduced some cognitive demands (e.g., some systems reduce memory demands by presenting work zone locations and temporary speed restrictions on in-cab displays), they also create new ones. These new cognitive demands, in turn, can lead to changes in how locomotive engineers operate the train. Sources of new cognitive demands include constraints imposed by the PTC braking profile that require locomotive engineers to modify train handling strategies; increases in information and alerts provided by the in-cab displays that require locomotive engineers to focus more attention on in-cab displays versus out the window, and requirements for extensive interaction with the PTC systems (e.g., to initialize it—to acknowledge messages and alerts) that impose new sources of workload. Although PTC technology is likely to have a positive impact on overall risk of accidents, these new sources of cognitive demand can contribute to errors and accidents (c.f., Wreathall et al., 2007).

Railroads and PTC system designers need to be made aware that measures can be taken in the design of PTC displays and in development of user training to improve train crew performance and reduce the potential for human error. The final section of this report discusses a number of suggestions for ways to improve in-cab displays to reduce cognitive demands on train crews and facilitate train crew performance as well as suggestions for improved training.

One promising area for research and development is improved in-cab displays that minimize the need to visually attend to the in-cab display to extract important information. It would be desirable to develop alternative display approaches for indicating to the locomotive engineer where train speed is in relation to the desired deceleration rate without having to closely monitor the visual in-cab display. Options to explore include the use of non-visual display modes, such as auditory or tactile displays. Heads-up displays, which would allow tracking critical driving parameters while still looking out the cab, may provide an alternative promising research direction.

A need also exists for improved training to support the introduction of new train control technologies. Training is needed to understand how the PTC system works (technical theory). Second, training is needed to understand how to operate the PTC system under different conditions (e.g., how to initialize it, what the different PTC displays mean, what error modes might arise, and what to do in those different conditions) and the applicable operating rulebook (PTC operations). Third, hands-on experience is required to reduce the attention demands associated with monitoring in-cab displays. A substantial learning curve exists to reach the point where the in-cab display does not serve as a source of distraction, diverting attention away from events out the window. Locomotive engineers must have sufficient experience in running a PTC-equipped train as part of training so that they get beyond the point where close monitoring of the in-cab display is required to avoid a penalty brake application. Fourth, hands-on experience and/or simulator training is required to learn the new train handling and braking strategies required to operate a PTC-equipped train to run efficiently while staying within the PTC braking profile (hands-on train handling). Hands-on experience is also needed to learn how to handle the "traps", challenging situations, and failure conditions that are known to arise in special circumstances.

Finally, train crews must avoid too much reliance on the new train control technologies. In particular, it is important to continue to run the trains without the PTC system activated. Therefore, if the system ever fails, the engineer will still be able to operate the train safely.

Two explicit limitations of the study should be noted. First, the PTC systems are described and analyzed as they were implemented at the time that site visits and interviews occurred (between 2002 and 2005). In some cases the PTC systems have undergone substantial modification since that time. Second, in evaluating the impact of PTC technology on locomotive engineer performance, we assumed that no change in train crew configuration would occur. This was the stated operating philosophy at the time we conducted the study. The analysis provided in this report does not explicitly consider any additional sources of cognitive workload that may arise should there be a transition to single person operations.

1. Introduction

Railroad operations in the United States are undergoing rapid changes. This includes introduction of faster trains (e.g., high speed trains on the Northeast Corridor (NEC)), increased demands on track usage, and new train control technologies such as positive train control (PTC).

As part of its efforts to investigate the safety implications of operational changes and emerging technologies, the Federal Railroad Administration's (FRA) Office of Research and Development sponsored a series of Cognitive Task Analyses (CTA) to examine the cognitive and collaborative demands associated with different railroad operations positions. The first CTA focused on railroad dispatchers (Roth, Malsch, and Multer, 2001). A second CTA addressed roadway worker activities (Roth and Multer, in preparation). The present report documents the results of a CTA that was conducted to examine the cognitive and collaborative demands and activities of locomotive engineers.

The purpose of the CTA of locomotive engineers was to understand the factors that complicate performance in today's environment and the knowledge and skills that locomotive engineers have developed to cope with the cognitive and collaborative demands placed on them. The goal was to develop a knowledge base that can be used as a starting point to inform the design of new technologies, human reliability analyses, and policy issues that may arise.

A primary aim of CTA was to identify and document cognitively challenging aspects of the current work so as to anticipate potential impacts of new technologies on locomotive engineer performance as well as provide guidance for their design and introduction. Of specific interest is the introduction of PTC technology. Railroads in the United States and Canada are developing a variety of PTC systems that are intended to improve the safety of railroad operations. Their goal is to prevent train-to-train collisions and protect train crews and roadway workers. This is accomplished by providing backup warnings to train crews and by stopping trains that are about to:

- Violate positive train separation (i.e., movement authority),
- Exceed speed restrictions (including civil engineering restrictions and temporary slow orders), and
- Enter track segments protected for roadway workers and their equipment operating under specific authorities.

An important aim of CTA was to identify cognitive activities that could be supported more effectively through the introduction of advanced technologies such as PTC technologies that are currently being developed by the railroad industry and evaluated as a part of FRA research and development efforts. A second, related, aim was to anticipate new sources of cognitive demands and complexities that the new technologies might pose. Although PTC technologies have the potential to improve safety and efficiency of railroad operations, they also have the potential to create new failure modes and impose new cognitive demands on locomotive engineers who need to monitor PTC displays and provide inputs to the system. Part of the objective of CTA was to understand these potential new performance demands.

While the report focuses primarily on the activities of the locomotive engineer, we recognize that train crews operating in the United States generally include two individuals, typically a locomotive engineer and a conductor. The report includes discussion of the interaction between the two individuals and how they work jointly to operate the train in a safe and efficient manner. It also includes discussion of the interaction of the train crew with other railroad personnel outside of the train (e.g., dispatchers, employee-in-charge roadway workers; crews of other trains.)

In evaluating the impact of PTC technology on locomotive engineer performance, we assumed no change in train crew configuration, since this was the stated operating philosophy at the time we conducted the study. The analysis did not explicitly consider any additional sources of cognitive workload that may arise should a transition to single person operations occur. Additional analyses would be needed to explicitly address the one-person operation case.

The next two sections provide a general introduction to cognitive task analysis and the types of information about locomotive engineer performance that it attempts to capture. Section 1.1 provides an introduction to cognitive task analysis methods and goals. Section 1.2 introduces a simplified model of the high-level cognitive functions and processes that underlie the cognitive performance of individuals and teams in natural work settings such as railroad operations. This model provided a guiding framework for eliciting and organizing the information that was used to analyze the knowledge and skills required of locomotive engineers and the factors that contribute to cognitive complexity.

Section 2 describes the methodology that was used to conduct CTA including the specific railroad sites that were visited and systems that were included in the analysis. The results of CTA are presented in Sections 3 and 4. Section 3 provides an overview of the cognitive demands and performance issues in current train operations. Section 4 discusses the likely impact of new train control technologies on cognitive demands and operating practice. Section 5 summarizes some of the key implications of CTA results for the introduction of new train control technology including design and training implications.

1.1 CTA Objectives and Approach

The need for a cognitive task analysis (CTA) arises from the changing nature of the locomotive engineer’s job over time. Since the beginning of railroad operations in the late 1800s to today, the locomotive engineer’s work has evolved from a physically demanding job to a cognitively demanding job.

CTA methods have grown out of the need to explicitly identify and take into account the cognitive requirements inherent in performing complex work (Potter, Roth, Woods, and Elm, 2000; Schraagen, Chipman, and Shalin, 2000; Bisantz and Roth, in press). A variety of specific techniques for knowledge acquisition have been developed that draw on basic principles and methods of cognitive psychology. These include structured interview techniques, critical incident analysis methods that investigate actual incidents that have occurred in the past, and cognitive field observation studies that examine performance in actual environments or in high fidelity simulators.

While a variety of methods for performing cognitive task and work analyses exist, they share a common goal of providing information about two, mutually reinforcing perspectives. One perspective focuses on the fundamental characteristics of the work domain and the cognitive demands they impose. The other focuses on how current practitioners respond to the demands of the domain. This includes a description of the knowledge and skills practitioners have developed to operate effectively as well as any limitations in knowledge and strategies that contribute to performance problems. The results of a CTA reveal (1) the factors that contribute to cognitive performance difficulty; (2) the knowledge and skills that expert practitioners have developed to cope with task demands; and (3) opportunities to improve individual and team cognitive performance in a domain through new forms of training, user interfaces, or decision aids.

The locomotive engineer CTA was performed based on a combination of structured interviews of individual and groups of locomotive engineers and conductors and field observations that included observations during head-end rides. Interviews and observations were performed in both passenger and freight territories. This included site visits to five territories where railroads were field testing advanced train control technologies. More details on the particular sites visited and groups interviewed can be found in Section 2.

The primary purpose of CTA was to identify and document cognitively challenging aspects of the current work so to anticipate potential impacts of new technologies on locomotive engineer performance as well as provide guidance for their design and introduction.

1.2 Cognitive Functions and Processes Underlying Performance

A CTA captures the knowledge and high level cognitive functions and processes that underlie individual and collaborative performance in natural settings (Crandall, Klein, and Hoffman, 2006; Klein et al., 2003). Examples of high level cognitive functions and processes include monitoring and detection, sense making, forming expectations, managing attention, planning, prioritizing and adapting plans as situations evolve.

Figure 1 provides a simplified model of the high-level cognitive functions that underlie performance of people in natural settings. This model was used to guide the collection and interpretation of information as part of the CTA. In this section we provide an overview of the model and illustrate it in a simple everyday example. In Section 3.2, we use the model to characterize the cognitive activities that underlie locomotive engineer performance and the factors that create complexities and increase cognitive demands.

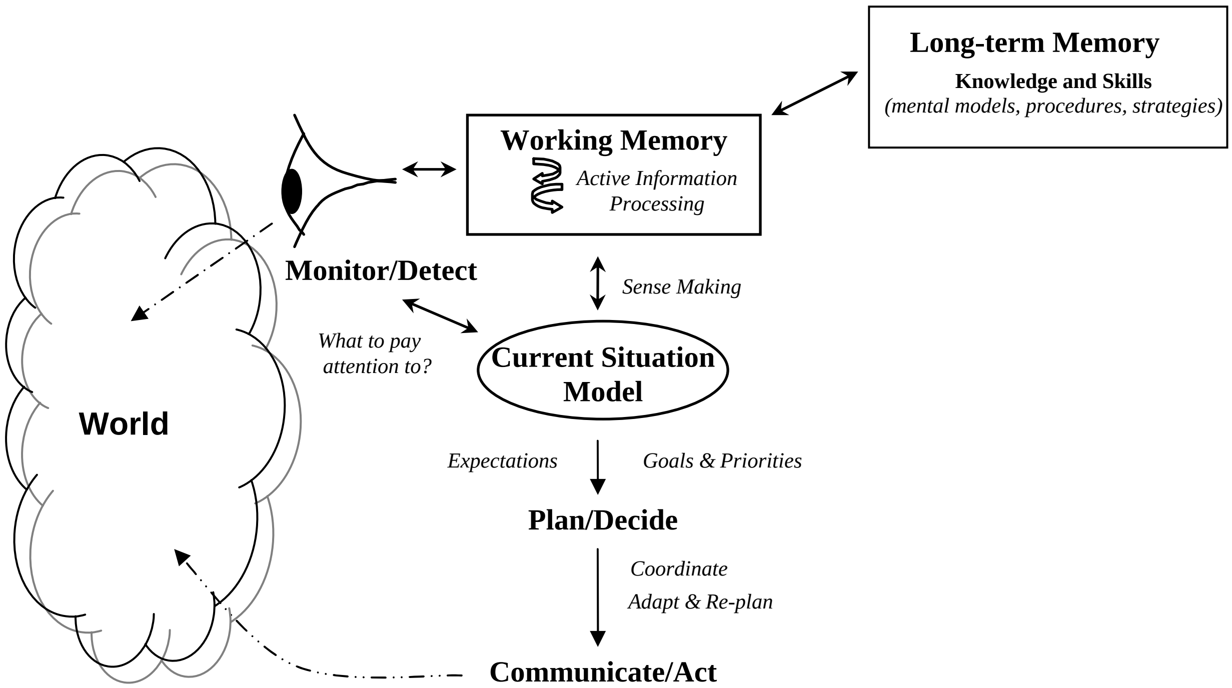

Figure 1. A simplified model of the knowledge, and high-level cognitive functions and processes that underlie cognitive performance

An important driver of performance is the *knowledge and skills* that individuals have developed with experience that is stored in long-term memory that allows engineers to rapidly recognize and respond to situations. This includes facts, mental models (e.g., mental model of how physical systems work), and strategies and procedures for how to accomplish tasks. Knowledge from long-term memory is combined with information obtained from direct perception of the world (through monitoring and detection) to interpret what is observed and develop a *situation model*, which represents the current understanding of the situation. This process is referred to as *sense making*. For example, if you see a group of kids in costume going door-to-door down the street and it is Halloween you might interpret the situation as a group of trick-or-treaters. The situation model is then used to generate *expectations* that can guide attention (where should I look?), provide the basis for *setting goals and priorities*, making *plans and decisions*, and taking action (including communicating). In the trick-or-treaters example, you might generate the expectation that the kids will soon ring your doorbell and decide to bring candy over by the door to be ready for them. A hallmark of cognition in natural settings is the ability of people to reinterpret and adapt to changing situations. In the trick-or-treaters example, when you open the door, you might see that the kids are soliciting donations for a charity and are not trick-or-treating for candy. In that case, you would try to adapt to the situation and look for coins that you can give out to the kids instead of candy.

Figure 1 provides a description of cognitive function at the *macrocognition level* (Crandall et al., 2006). The emphasis is on describing people's knowledge and strategies and how these are used to guide formation of expectations, development of plans, and adaptation of plans when events differ from expectations.

Cognitive performance can also be characterized at a more microlevel, in terms of the elemental mental structures and processes involved from the point that external information is first detected by the sensory system until a response is produced by the motor system. For example, a microcognition description would provide a detailed characterization of how information moves across mental structures, such as sensory buffers and short tem memory stores and the detailed computational processes by which they are transformed. In Figure 1, this more detailed level of cognitive processing is represented by the arrows linking the "eye" icon (representing sensory processes), the box labeled "working memory," representing information processing activities that occur in working memory, and the box labeled "long-term memory" that represents the processes by which information from long-term memory is activated and retrieved.

Macrocognition and microcognition approaches provide complementary perspectives. Numerous attempts have examined the micro second-by-second information processing involved in driving a route. Examples include Luke, Brook-Carter, Parkes, Grimes, and Mills (2006) who employed eye tracking recordings to analyze the detailed visual scanning strategies used by locomotive engineers; Jansson, Olsson, and Erlandsson (2006) who used think-aloud protocols to examine the moment-by-moment attention and thinking processes as locomotive engineers drove a train route; Gillis (2005) who examined the detailed serial and parallel mental processes, and how they vary over the time course of a train trip; and Hamilton and Clarke (2005) who developed a computational model intended to predict locomotive engineer workload and performance time for different routes.

The present CTA provides a more macrocognitive analysis of the performance of locomotive engineers. It provides a higher level picture of the contextual factors that impact performance and the cognitive and collaborative strategies that domain practitioners have developed in response to work demands. McLeod, Walker, and Moray (2005) have argued that this level of analysis is necessary to understand the critical factors that influence actual performance in a real-world, real-time, environment. This includes factors that contribute to error as well as factors that contribute high reliability performance and resilience in the face of unanticipated conditions (Hollnagel, Woods, and Leveson, 2006; Roth, Multer, and Raslear, 2006).

A macrocognitive level of analysis can provide useful insights into the factors in today's environment that pose challenges and create opportunities for error. It can point to opportunities for how new technologies could more effectively support performance. It also provides insights into aspects of the current environment that provide effective support and support functions that should be preserved as new technology is introduced. Existing approaches to analyzing and modeling driver performance based on microlevel information-processing models and hierarchical task decomposition do not capture these contextual and situational factors (Crandall et al., 2006; Klein et al., 2003).

2. Methods

CTA was based on an extensive series of interviews and observations that were made at seven sites between February 2000 and September 2005. These sites included intercity passenger, commuter, and freight operations.

Initial interviews and observations were conducted on Amtrak passenger trains in 2000. The objective was to obtain a high level overview of the knowledge, skills and cognitive demands associated with operating a train. A total of 11 locomotive engineers were interviewed that included: (1) training instructors and experienced locomotive engineers at the Amtrak Simulator Training Facility in Wilmington, DE; (2) locomotive engineers during head-end rides that were conducted on NEC signal territory, as well as unsignaled (dark territory) outside NEC.

Topics covered during this initial series of interviews and observations included:

- Training and knowledge requirements,
- Activities conducted at a start of a shift and at shift turnovers,
- Responsibility distribution and coordination when two people in the cab,
- Cognitive demands,
- Establishing priorities/managing workload,
- Planning/decision making strategies (including train handling and braking strategies),
- Radio communication,
- Strategies for maintaining (situation awareness/knowing where you are), and
- Fatigue/ways to respond to/cope with fatigue.

A second series of interviews were then conducted that focused specifically on the introduction of advanced train control technologies and their potential impact on train operation. Interviews were conducted at five sites where railroads were testing or beginning to use new train control technology with elements of PTC. Table 1 lists the railroads and systems examined. The objective was to understand the perceived impact of the new train control technologies on how the locomotive engineers ran the trains, and whether any new human performance issues or sources of risk were associated with the use of these new systems.

Topics covered included:

- Required interactions with the system both during set up before a trip as well as during a trip,
- The potential impact on distraction (attention allocation between information inside and outside the cab),
- Impact on train handling and braking strategies,
- Impact on workload and work mode transitions,
- Training,
- Complacency,
- Support for look-ahead,
- Impact on memory requirements (reliance on information in the head vs. on paper vs. integrated in the cab interface), and
- Potential interaction with operating rules.

Table 1. New Train Control Technologies Examined

System Name	Railroad Interview Date	Groups Interviewed
Communications Based Train Management	CSX October 2001	locomotive engineers, conductors, includes observations during head-end rides
North American Joint PTC System	Amtrak Union Pacific October 2002	locomotive engineers, training instructors; includes observations during head-end rides
Incremental Train Control System	Amtrak October 2003	locomotive engineers; includes observations during head-end rides
Advanced Speed Enforcement System	New Jersey Transit March 2004	locomotive engineers, conductors
Electronic Train Management System (ETMS)	BNSF (Beardstown, IL Subdivision) September 2005	locomotive engineers, training instructors; includes observations during head end rides

Interviewees were recruited through contacts with railroad management and labor union representatives. Interviews were conducted with individuals or groups of up to five people representing a single craft. Typically two to four interviewers represented different behavioral research disciplines, including human factors engineering and human reliability analysis. One interviewer led the interview sessions using a set of predefined interview questions. The other interviewers took notes and asked occasional follow up questions. The predefined question set primarily served as a checklist of topics to be covered. Actual questions asked and their order varied depending on participant responses.

Interviews lasted approximately 2 hours and were tape recorded with the knowledge and permission of the individuals who were interviewed.

The tape-recorded interviews were transcribed and analyzed with the goal of identifying recurrent themes across interviews as well as specific actual incidents described by interviewees that illustrate the themes.

The analysis focused on identifying: cognitive and collaborative demands in the current environment, which contribute to performance difficulties and errors; and skills and strategies that expert practitioners have developed to build and maintain shared situation awareness to avoid or catch errors and to improve efficiency and enhance safety.

As part of the analysis, common themes relating to the impact of the introduction of new technologies were also extracted. This included examination of new opportunities to enhance performance and/or improve safety through the introduction of new technologies, as well as concerns relating to potential new problems that could emerge with the introduction of new technologies.

The interviews of locomotive engineers, relating to the impact of PTC technology, were conducted as part of a larger project that addressed the impact of PTC technologies on railroad personnel performance and reliability. That project included interviews with roadway workers and dispatchers as well as train crews. A more detailed description of the methods and results are reported in Wreathall, Roth, Bley, and Multer (2007).

3. Cognitive Demands and Performance Issues in Current Train Operations

This section describes the cognitive demands and activities of locomotive engineers as they relate to current train operations. Section 3.1 provides a general introduction to train crew roles and responsibility. Section 3.2 examines the cognitive functions that underlie locomotive performance and the factors that contribute to cognitive challenges including:

- The need to maintain broad situation awareness and develop an accurate current situation model,
- The need to generate expectations, to think ahead, to guide attention, and to prepare for anticipated actions as well as plan for contingencies,
- The need to actively engage in sustained visual and auditory monitoring including monitoring radio communication,
- The need to manage multiple demands on attention, and
- The need to prioritize and manage multiple goals.

Section 3.2 also covers the knowledge and skills that experienced locomotive engineers develop that allows them to operate safely and efficiently including train handling strategies that are adapted to locomotive and train consist[1] characteristics, the terrain, and the automated train control technologies

This section analysis focuses primarily on train crew roles and responsibilities in passenger train operations. In many cases, the same cognitive tasks apply to freight operations as well. Cases having significant divergence in roles, responsibilities, or cognitive demands experienced are explicitly noted.

3.1 Train Crew Roles and Responsibility

Train crew roles and responsibility vary between passenger and freight operations.

3.1.1 Passenger Operations

In Amtrak passenger train operations, a crew consists of a minimum of three employees: a locomotive engineer, a conductor, and an assistant conductor. The locomotive engineer operates the train and complies with signals and speed restrictions. The conductor is in charge of the train. He/she will insure that doors are closed and that it is safe to move. The assistant conductor assists with fare and ticket collection. In an emergency, he/she is responsible for passenger safety.

Generally, two individuals, two locomotive engineers or an engineer and a conductor, are required in the cab. The primary exception arises on short runs of 6 hours or less in signal territory on the NEC. In those cases, a single locomotive engineer may operate the train. However, if three or more of the hours fall between midnight and 6 a.m., then operating rules require two people in the cab. Similarly, if the train goes through dark territory where train

[1] A train consist means one or more locomotives coupled to rail cars.

control is accomplished via radio communication with the dispatcher, then two individuals are required in the cab.

Passenger trains that require two individuals in the cab will typically use two locomotive engineers. They share responsibility for operating the train. The two engineers will usually arrange between themselves how long each will operate the train before relinquishing controls to the other engineer. They will typically divide it either by time or by distance. The individual who is not currently driving the train is required to remain vigilant. He/she still has responsibility to insure that all the rules, signals, and speed restrictions are complied with. Typically, both engineers will call out the signals as they approach them. In dark territory, the engineer, who is not operating the train, is responsible for communicating with the dispatcher and writing down track warrants.

Responsibilities of the conductor on passenger trains include:

- Communicating with the dispatcher,
- Insuring the engineer complies with track warrants,
- Repeating back track warrants verbally to the engineer ,
- Preparing to leave the station, the conductor reminds the engineer of the next speed restriction,
- Coordinating with the engineer on where to stop the train so that the cars are on the platform (This is often done during the pre-brief conducted prior to the start of a run),
- Informing the engineer that it is okay to go (leave the station),
- Coupling and uncoupling cars,
- Changing switch position,
- Coupling hoses to take cars apart and put together,
- Ticketing and primary responsibility for passengers, and
- Communicating with dispatcher on issues associated with customer, passenger, revenue, lost baggage, food.

On passenger trains, the conductor spends his/her time in the passenger cars. The conductor and engineer typically communicate via radio. When the train has an intercom, the conductor presses a button located at the end of the car, rather than use the radio. When the conductor pushes the button twice and a buzzer sounds in the cab it tells the engineer they are ready to go after making a station stop. In cases where the conductor is off the train (e.g., to control a manual switch), they can communicate via hand signals. Both the conductor and the engineer can communicate with the dispatchers.

3.1.2 Freight Operations

In U.S. freight operations, two individuals work in the cab; a locomotive engineer who is responsible for running the train, and a conductor who is in charge of the train. The conductor is in charge of the train consist and is responsible for any required manual control of switches. The conductor shares the workload and serves as a backup to detect and recover from errors. The responsibilities of the conductor include the following:

- Handle radio communications, therefore relieving the locomotive engineer of this potential source of workload.

- Provide reminders of temporary speed restrictions, work zones, and end-of authority blocks coming up. For example, the conductor would remind the locomotive engineer when the radio frequency changed (such as when transitioning from one railroad's territory to another). In this way, the conductor serves to remind the locomotive engineer of important mode transitions.
- Manually lines switches when moving in and out of a siding. This requires that the conductor get off the train, align the switch for the siding, wait for the train to pass, manually realign the switch for the mainline, and then walk to the front of the train.
- Be responsible for the train consist.

The conductor is responsible for checking to make sure that the engineer is aware of relevant information related to operating the train. If the conductor isn't sure that the engineer is aware of something or is under control, he/she is expected to say something. The locomotive engineer can also catch and correct errors made by the conductor. An example was given where a train was in a yard. The conductor told the locomotive engineer that he had a "restricted proceed" signal, when in fact the train was supposed to stop. The locomotive engineer was more experienced and recognized that you don't get restricted proceed signals in a yard. He questioned the conductor and discovered the error.

3.2 Knowledge and Cognitive Functions involved in Operating a Train

Figure 2 provides a model of some of the major cognitive functions and processes that underlie locomotive engineer performance when operating a train. It is adapted from a model of train engineer performance developed by McLeod, Walker, and Moray (2005). It contains the same basic high level cognitive functions depicted in Figure 1, with more detail provided on the specific knowledge and cognitive functions relevant to locomotive engineer performance. This model has been used as an organizing framework for synthesizing and presenting the results of the CTA with respect to cognitive functions involved in operating a train and the challenges that arise.

The results of the CTA support this model of locomotive engineer performance. The results illustrate the knowledge and skill that allow locomotive engineers to operate trains safely and efficiently in today's environment and point to ways new technologies, such as new train control technologies, can support performance as well as introduce new sources of cognitive demand. A high level summary is provided below of the elements of the model and how they combine to guide the performance of locomotive engineers. The sections that follow will provide more details with respect to some of the major cognitive elements and challenges that affect locomotive engineer performance.

As depicted in Figure 2, *operator knowledge and skills* provide the foundation underlying operator performance. These include knowledge of the physical characteristics of the route (e.g., track grade; physical landmarks) and knowledge of train handling characteristics (e.g., characteristics of specific locomotives). They also include knowledge of the train schedules, operating rules and procedures, and informal practices based on organizational culture. In addition, they include skills and strategies developed through training and experience, such as train handling strategies that are fine-tuned to the route and the particular train characteristics that have been built up from experience.

This long-term knowledge combines with current information obtained from direct perception (e.g., displays inside the cab as well as the scene outside the cab) to produce a *situation model* of the current state of the world as it affects the current train handling activity (Figure 2). Key elements of the situation model include information about current time and location, physical surroundings (e.g., weather, track grade and conditions, milepost, landmarks, and signals) as well as information about other key agents in the environment that might impact safety (e.g., other trains in the vicinity, roadway workers, passengers, pedestrians, motor vehicles, and trespassers). It also includes information about factors that constrain or prescribe action (e.g., speed limits, signal aspects, and dispatcher directives).

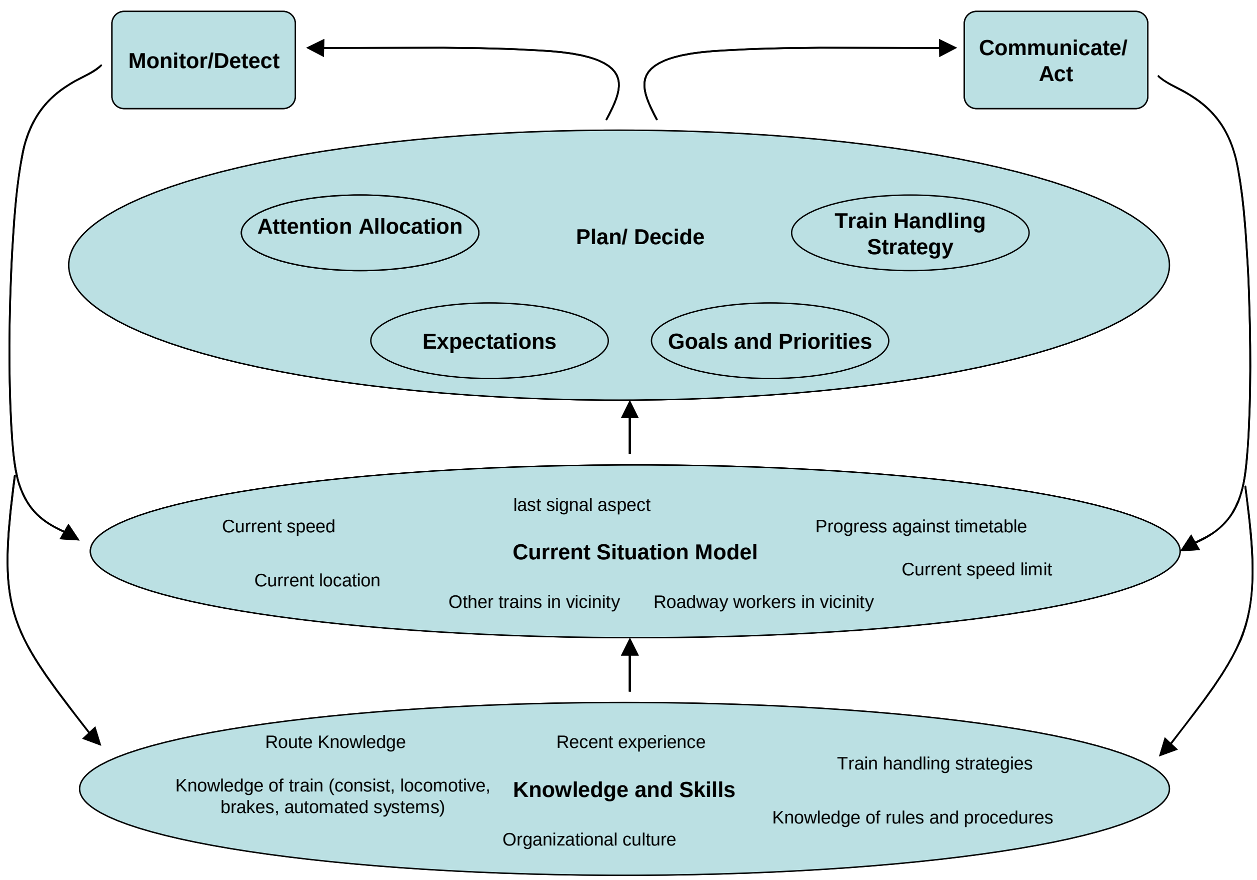

Figure 2. Simplified model of the knowledge, and cognitive functions and processes that underlie locomotive engineer performance

The situation model provides the basis for *planning and deciding* (Figure 2), which includes forming expectations, generating and prioritizing goals, deciding where to focus attention and planning what actions to take. For example, knowledge of the route, as well as the last signal aspect, can lead to expectation of upcoming speed restrictions or requirements to stop. Knowledge of roadway workers being in the vicinity might lead to expectations of roadway workers ahead. In turn, these expectations will influence attention allocation, action prioritization, and train control decisions (e.g., to focus attention outside the cab to look for roadway workers; to prepare to start braking action to slow down the train; or to prepare to blow the horn). The planning and decision making processes result in production of specific actions such as changes in train speed, application of brakes, blowing the horn, or communicating with others (e.g., a dispatcher and/or roadway foreman). In turn, the actions (and feedback) result in updates to the situation model as well as updates to the long-term knowledge and skills.

The next sections provide more details with respect to some of the major cognitive functions and challenges that affect locomotive engineer performance.

3.2.1 Developing and maintaining a situation model

Developing and maintaining situation awareness represents one of the locomotive engineer's core cognitive functions. The term situation awareness is formally defined as the perception of the elements within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future (Endsley, 1995). It emphasizes the ability of people to continuously extract environmental information, integrate this information with previous knowledge to form a coherent mental picture, which we refer to as a situation model, and use that situation model to further perception and anticipation of future events (Dominguez et al., 1994; Endsley, 1995).

In the context of operating a train, elements of situation awareness include awareness of:

- Current location, which includes knowing exact location (e.g., within tenths of a mile) as well as where they are relative to territory boundaries (e.g., where they are relative to their movement authorities, and in which railroad territory they are),
- Physical characteristics of the track that will impact train speed and braking requirements (e.g., track grade and physical condition of the track),
- Fixed physical elements in the vicinity that support knowing where you are and influence running of the train (e.g., physical landmarks, mileposts, grade crossings, and stations),
- Dynamically changing physical elements that impact running of the train and safety (e.g., location of temporary speed restrictions and location of work zones),
- Location of trains and roadway workers in the vicinity,
- Location of trespassers and potential hazards (e.g., children throwing stones),
- Applicable speed restrictions and related restrictions (e.g., signal aspects and temporary speed restrictions),
- Current speed relative to applicable speed restrictions,
- Current position relative to schedule,
- Transition points/mode transitions that signal changes in how the train should be operated, and
- Characteristics of the locomotive and train consist (tonnage and length) that will impact train handling and braking.

Jannsson, Olsson, and Erlandsson (2006) identified three distinct locomotive engineer train operating situations that involved different considerations in train handling. These were (1) *out on the route,* between two stations where the engineer is focused on the speed limits and on adjustment of the speed of the train; (2) *approaching a station*, where the engineer's attention shifts to monitoring the surrounding environment for people on the platform, trains coming the other way, signals, and braking decisions relative to position of the platform that come into play; and (3) *leaving a station*, where the engineer is focused on leaving the station as safely and quickly as possible to maintain schedule.

Our CTA suggests that a broader number of distinct operating mode conditions and transitions are likely to be between operating modes that influence the set of considerations that impact train operation. These additional operating modes and transitions include:

- *Approaching a grade crossing,* where a need exists, to monitor for pedestrians and road cars and to blow the whistle to alert them;
- *Approaching a work zone,* where a need exists, to stop and obtain permission from the roadway worker in charge to enter;
- *Crossing a work zone*, where a need exists, to monitor for presence of roadway workers or equipment on the track and to maintain awareness of limits of authority both with respect to location and time expiration;
- *Approaching an area where roadway workers are working on the side of the track,* and a need exists to monitor for incursion onto the track and blow the whistle to alert them;
- *Transitioning between railroad territories* that may signal a change in operating rules and/or a change in radio frequency for communication with the dispatchers, other trains, or roadway workers; and
- *Transitions in the methods of train operation,* for example, in the case of new PTC technologies, train operation may differ when the PTC system is operating and when it is not operating.

Knowledge of the current location is critical to locomotive engineer performance, because applicable speeds, authorities, and actions (e.g., braking, blowing whistle) depend on location. Locomotive engineers indicated that at all times they must know exactly where they are located to within a 10th of a mile. Complications include traveling at night and in inclement weather where visibility outside the cab is low. In addition, mileposts and other signage can be removed, defaced by vandals, or obscured (e.g., by foliage).

With experience, locomotive engineers develop detailed knowledge of landmarks that provide rapid visual cues to location (e.g., familiar trees, houses, and bridges). A locomotive engineer said, “You’ll notice there is a certain house right before this interlocking or a golf course. You just see the territory so much that you equate certain landmarks with certain things that happen on the railroad.”

Locomotive engineers also indicated that they get haptic cues of location (e.g., vibrations associated with portion of track and curves) as well as sight, sound, and even smell (e.g., near a farm). One locomotive engineer indicated that, “Even if you closed your eyes and you didn’t see the territory you could know by the sounds and feels where you are.” “Now that is another thing that experience brings—the feeling”, he said. “I’m going over the Mystic River Bridge because of that clack, clack, clack noise.”

In addition to being aware of their own location, locomotive engineers actively engage in monitoring and communication strategies intended to develop and maintain situation awareness with respect to the location of other trains, roadway workers, trespassers, and other potential hazards in their vicinity. These active monitoring and communication strategies contribute to the overall safety and resilience of the railroad system. These strategies are described more fully in Sections 3.3.3 and 3.3.4.

3.2.2 Generating Expectations and Thinking Ahead

Experience allows locomotive engineers to build a mental picture of what to expect along the route. This enables them to anticipate what is upcoming and what actions will be required to guide, where to pay attention, and to rapidly focus attention on the unexpected and abnormal (e.g., a trespasser on the track). Being able to anticipate and plan ahead is particularly important in railroad operations where—because of the inertia of the train—locomotive engineers may have to initiate action early.

Engineers explained that the majority of their attention is focused on anticipating what is likely to be up ahead and what actions it will require. A locomotive engineer stated, “What I’d be thinking about is not how fast I am going right now, or where I’m at right now, I’d be more interested in where I was going and what I had to be doing speedwise when I get to that point—what is next.”

Often the locomotive engineer will need to take action (start to brake or blow the whistle) in advance of (and in some cases in absence of) visual cues. One locomotive engineer mentioned that places, such at a curve, you can’t see a crossing, and in turn, the people at the crossing cannot see the train. In those situations, the engineer needs to know that the crossing is upcoming and to sound his whistle before going round the turn. Similarly, locomotive engineers need to maintain awareness of the length of the train and where the rear of the train is relative to key transition points. For example, they need to be aware of when the rear of the train clears a temporary speed restriction zone.

Being able to anticipate what is likely to be up ahead and take preparatory action depends on developing an accurate situation model that combines information built from experience (e.g., long-term knowledge of the physical terrain including information on track grade) with information about current situational factors and constraints. This includes awareness of environmental factors (e.g., leaves on the rails making them more slippery or fog reducing visibility), location and activities of other entities in the vicinity (other trains, roadway workers, pedestrians), and situation specific restrictions (e.g., temporary speed restrictions and work zones that require permission from the roadway worker in charge before entering).

Locomotive engineers constantly draw upon their mental model to project into the future and determine what actions to take. For example, in determining train speed, the engineer must not only consider current train speed restrictions, but speed restrictions that are in place ahead. Similarly, locomotive engineers draw upon their mental models to guide where to direct attention. One locomotive engineer explained it this way:

> “I’m at milepost 56; my speedometer tells me I’m doing 90. I’m ‘allowed’ to get up to 125, let’s get to 125, now when do I have to get to below 125? That’s what I’m looking for next. Where’s my next station? Do I have any temporary speed restrictions? Is there anything between here and there on this track that I have to be worried about? I look at the bulletin order—is there anything in the bulletin order that tells me that there are guys working out here that I have to be prepared to look at for guys working on the track?”

Decisions that depend on projecting into the future include at what speed to travel, when to start to brake and how quickly, and when to sound the horn. In addition, the locomotive engineer may anticipate what track he or she will need to be on at the next station and what actions are required now to position themselves to move efficiently, without undue delays. One locomotive engineer provided the following example:

> "If I'm going to switch from one track to the other, let's say there are four tracks, two inside tracks and two outside tracks. The inside tracks don't make station tracks. If I'm on an inside track and I know I have to make a station stop up ahead, I want to make sure that I am going to get over to that track to make a station stop. If I don't, I'm going to have to stop my train and tell them, 'hey look, I'm going to have to make my station stop and I can't do it from here, are you going to give me special permission to do it from here, or am I going to have to wait for you to line me up to make that stop?'"

3.2.3 Monitoring and Detection

One of the locomotive engineer's primary responsibilities is to monitor activity outside the cab to detect and respond to unanticipated events. The engineers' mental model allows them to anticipate what to expect along the route, it guides attention allocation and allows them to rapidly focus attention on the unexpected and abnormal (e.g., a trespasser on the track).

The locomotive engineer's primary monitoring channels are visual and auditory. The visual channel involves monitoring displays inside the cab as well as the environment on and around the tracks outside the cab. The auditory channel primarily involves monitoring and participating in communication over radio channels.

3.2.3.1 Visual Monitoring

The locomotive engineer has a number of displays to monitor inside the cab related to control of the train. These include, monitoring speed indicators, brake pipe and brake cylinder gauges, and amperage gauges. In addition, there may be in-cab signal displays that provide indication of the signal aspects that dictate train movement and speed. New advanced train control technologies, such as PTC technologies, have added additional in-cab monitoring demands. For example, PTC systems may include displays that indicate desired braking profile and target values (e.g., target speeds or braking distances) beyond which automatic train braking will occur. (See Section 5 for more details).

Although monitoring in-cab displays is important to ascertain train speed and control status, monitoring outside the cab is equally or more important. Engineers need to monitor for anticipated items such as changes in track grade, track signals, mileposts, signs, work zones markings, sidings, stations, and grade crossings. They also need to monitor for unanticipated objects. This includes signal aspects that are unexpected (e.g., that vary from the usual); signposts that are unexpected (e.g., a temporary speed restriction or work zone sign that had not been otherwise communicated); obstacles on the track such as animals, debris, discarded objects (e.g., refrigerators), individuals on or around the track (e.g., trespassers, roadway workers, people and vehicles at grade crossings), problems with the track (e.g., broken rails and misaligned switches), and other trains that are unanticipated (e.g., a train that is stopped on the track or coming in the opposite direction.).

Being able to detect and recognize violations of expectations is one of the critical cognitive functions for safe train operation. However, often attention is driven by expectation, resulting in potential for error when unexpected conditions arise (e.g., failure to detect work zone sign, in the case where they had not been informed to expect a work zone). Consequently, as mentioned previously, locomotive engineers work hard to extract information allowing them to accurately anticipate upcoming events. For example, as described in the next section, they actively monitor the radio to anticipate the location, direction of movement and activities of trains and roadway workers in their vicinity. They also work actively to maintain awareness of the location of trespassers and obstacles on the track.

3.2.3.2 Monitoring Radio Communication

Locomotive engineers rely heavily on radio communication to extract relevant information to update their situation model, anticipate upcoming events, and plan ahead. They extract information from messages addressed explicitly to them, as well as messages addressed to others but relevant to the safe and efficient operation of their train.

The locomotive engineers monitor the radio to extract information about the location and activities of roadway workers and other trains in the vicinity. A locomotive engineer explained:

> "Your listening skills improve. You listen to the radio even though they may not be talking to you. You may get a clue of what is going on by listening to the conversation on the radio. You know there is a workgroup up ahead, so you should be on the lookout for workers on the rail or maybe equipment on the rail. You want to turn your head light down. Start making noise with your whistle and horn to alert the people that you are coming."

Monitoring radio communication is valuable for building an accurate situation model of activity in the vicinity. It also provides a means of catching errors with potential safety consequences. One engineer provided an actual example that illustrates this point. He described a case where a dispatcher (erroneously) told a locomotive engineer that his track was protected, when in fact it was not. The locomotive engineer was able to catch the error by overhearing radio communication between the dispatcher and a second locomotive engineer. He overheard the dispatcher give the second locomotive engineer permission to cross the track. The (first) engineer immediately realized the dispatcher had made an error and was able to head off a potential collision by contacting the dispatcher over the radio.

The results highlight the active strategies that train crews use to extract relevant information by "listening in" on radio communications directed at others. These active listening processes enable individuals in the distributed organization to identify information that has a bearing on achieving their own goals or maintaining their safety. Therefore, they can recognize situations where information in their possession is relevant to the performance or safety of others. Similar results have been observed for roadway workers and dispatchers.

The results reinforce findings from other domains (e.g., space shuttle mission control, air traffic control, air craft carrier operations) regarding the importance of listening in on shared communication channels for supporting anticipation, contingency planning and catching and recovering from error (Luff, Heath, and Greatbach, 1992; Patterson, Watts-Perrotti and Woods, 1999; Rochlin, La Porte, and Roberts, 1987; Smith, McCoy, and Orasanu, 2000).

In addition to actively monitoring radio communication to extract relevant information, locomotive engineers routinely engage in informal communication practices intended to enhance shared situation awareness among train crews, dispatchers and roadway workers and improve overall system safety. This is discussed more fully in Section 3.2.4.2.

3.2.4 Communication

Train crews communicate with dispatchers, other trains, and roadway workers over two-way radio. In many cases, formal operating rules prescribe the form and content of the information to be communicated. Observations and interviews revealed additional informal, proactive communication practices, which have emerged that serve to increase efficiency of railroad operations as well as enhance overall safety.

3.2.4.1 Formal Communication Prescribed by Operating Rules

Communication requirements depend on the signaling systems and operating rules in place. For example, under centralized traffic control, train movement is governed by signals, so no verbal communication with dispatchers is required as long as no system malfunctions occur. In dark territory, where no signals direct train movement, train movement authorities are provided through verbal communication between train crews and dispatchers over two-way radio.

Communication between train crews and dispatchers also arise when problems occur with the signal system or new temporary speed restrictions arise that dispatchers need to communicate to the train crews.

Formal operating rules dictate the form and content of the information exchanged during these transactions. For example, in dark territory, a train crews will call the dispatcher to request authority to enter a portion of track referred to as a block. The dispatcher will enter into a computerized database the mileposts designating the start and end of the portion of track being authorized for the authority. The dispatcher will then read the information off of the computer screen to the train crew, who are required to enter the information by hand onto a paper authorization form and then read the information back to the dispatcher. The dispatcher confirms that the information read back is correct, and only then is the authority to occupy and work on that portion of track put in place.

Train crews are required to contact roadway workers to obtain authority to enter work zones. In those cases, the train crew is required to contact the employee in charge via radio to obtain approval to enter the work zone. As in the case of obtaining authorities from dispatchers, the train crew uses a formal communication protocol when obtaining authority to enter a work zone from the employee in charge. This protocol involves documenting and reading back the authority received.

Federal radio rules prohibit the locomotive engineer, who is engaged in operating a train, to take directives over the radio. As a consequence, unless the train is stopped, radio communication is handled by the conductor.

Communication is also required between the locomotive engineer and the conductor. Crew members are required to communicate signal aspects to each other.

3.2.4.2 Informal Communication to Enhance Shared Situation Awareness

In addition to formally prescribed communication, numerous informal, cooperative communication strategies will enhance situation awareness and improve safety by alerting each other (e.g., train crews, MOW crews, and dispatchers) of potential safety hazards. This informal communication helps train crews anticipate upcoming events and potential hazards so that they are in a better position to catch and prevent problems. The following are some examples of informal communication observed during interviews of locomotive engineers and conductors.

Dispatchers will call trains to alert them to unusual conditions that vary from their regularly expected routine. In particular, a case was observed in the NEC where the dispatcher called a locomotive engineer to alert him that he was approaching an unexpected signal and should prepare to stop. This event occurred because a train was stopped ahead. The dispatcher did not need to call the locomotive engineer because the signal aspect should have been sufficient to direct the train to stop. However, the dispatcher provided this redundant cue to reduce the possibility of error. The redundant cue served an important safety function. By alerting the locomotive engineer to the upcoming signal aspect, the dispatcher reduced the possibility that the engineer would miss the signal (because the engineer was not expecting it). Further, by explaining the reason for the signal aspect, he avoided the possibility that the locomotive engineer would wonder whether the unexpected signal aspect was a false signal. The dispatcher referred to the communication as a "courtesy." We found that dispatchers, train crews, and roadway workers routinely engage in informal communication for the sole purpose of enhancing each other's situation awareness. They routinely call these communications courtesies, but they clearly play an important role in enhancing overall safety and resilience of the railroad system (Roth, Multer, and Raslear, 2006).

Locomotive engineers actively engage in communication to improve awareness of the location and activities of other trains and roadway workers in their vicinity. They will routinely call other trains in the vicinity to find out where they are and to alert them to potential hazards, such as trespassers, kids throwing objects, and problems on the track. They will also call to inform each other of the location and activities of roadway workers in the vicinity.

One locomotive engineer explained that he routinely wrote down what trains were in the vicinity, which trains he expected to pass, and where he expected to pass them. He explained that one reason he did this was in case he saw something that was important to communicate. As an example, if kids were on the track, then he would want to alert other trains in the vicinity.

The engineers mentioned that it was the dispatcher's job to inform them of the location of other trains, but that they actively sought that information through direct communication with the other trains as a redundant safety check. As one locomotive engineer explained, "I imagine that dispatchers get busy too and things happen and there might be something they get wrapped up in and they can't communicate everything."

The results highlight the active cooperative processes that train crews, dispatchers, and roadway workers engage in that enhance shared situation awareness and the overall safety of railroad operations (Figure 3). The active work that locomotive engineers engage in to build and update a mental model of the location and activities of others in the vicinity is consistent with the behavior we have observed of individuals from other railroad crafts including dispatchers and roadway workers (Roth, Multer, and Raslear, 2006). Also consistent with observations in other railroad crafts, including dispatchers and roadway workers, is the emergence of cooperative communication practices that go beyond the requirements of formal operating rules. These informal, proactive communication practices foster shared situation awareness, facilitate work and enhance on-track safety. Interestingly, these communication practices were frequently referred to as courtesies highlighting their optional nature and positive contribution.

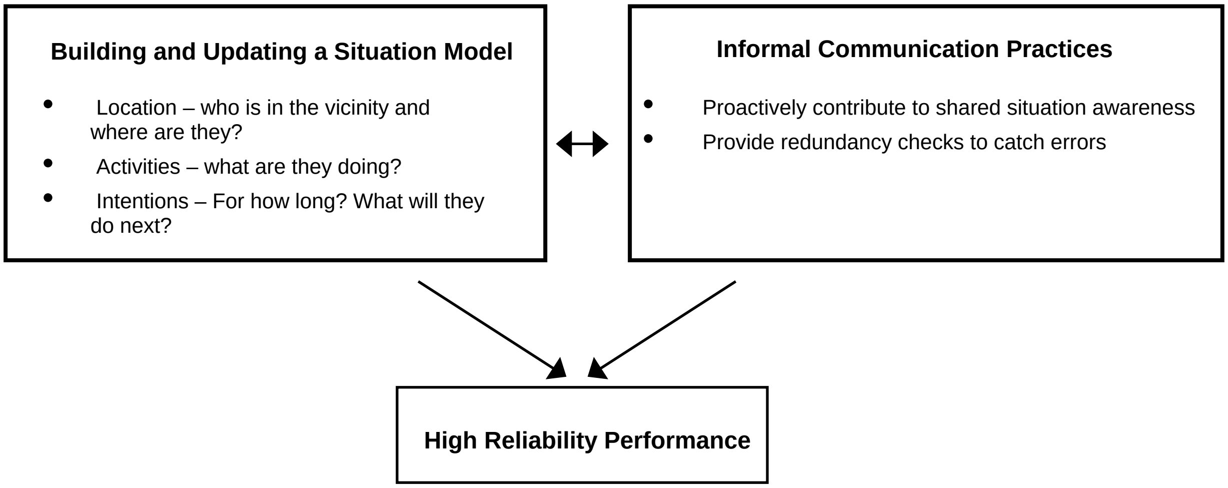

Figure 3. Framework showing how informal cooperative processes across distributed teams build on and contribute to shared situation models and how the two combined can foster higher reliability performance and increased safety

The results build upon and extend the literature on teamwork and the role of shared situation awareness in facilitating work and enhancing safety. They reinforce the view that informal practices of domain practitioners can contribute substantively to system resilience and safety (Hollnagel et al., 2006). This view contrasts with the more traditional perspective that emphasizes humans as a source of error that can degrade an otherwise safe system.

3.2.5 Planning and Decision making

Much of the train crew's behavior is governed by operating rules, train schedules, signals, and track authorities. These dictate train movement, including what track to operate, maximum speed, and when and where to stop.

Primary locomotive engineer decisions associated with operating the train relate to (a) allocation of attention, (b) train handling strategies that relate to control of speed and braking, and (c) when and where to blow the whistle.

These decisions depend on prioritizing and managing multiple goals related to operating efficiently while maintaining safety.

3.2.5.1 Prioritizing and Managing Multiple Goals

Cognitive performance is goal driven. Locomotive engineers must balance two primary goals: operate efficiently and operate safely.

The engineer must be concerned about the safety of the crew, passengers, consist, as well as the safety of individuals in the vicinity of the train. These individuals include roadway workers that may be working on and around the track, passengers and pedestrians that may be walking by or crossing the track, and other vehicles (e.g., high rail cars on the track and road vehicles at grade crossings).

Efficiency of operation is a second primary goal. This goal includes staying on schedule, and operating the train in a way that minimizes equipment wear (e.g., wear on the brakes) and fuel usage. In the case of passenger trains, it also includes considerations such as passenger comfort (e.g., by braking smoothly). Under some conditions, these multiple goals may conflict with each other, requiring the engineer to make decisions that balance the multiple goal constraints.

3.2.5.2 Establishing Priorities/Managing Demands for Attention

Often multiple competing demands occur for the attention of locomotive engineers.

These include:

- The need to monitor for and respond to events outside the cab. Events outside the cab that require attention include anticipated events such as an upcoming station, speed restrictions, work zones or grade crossings grade changes, signage, as well as unanticipated events such as trespassers or obstacles on or near the track;
- The need to monitor and respond to displays and equipment inside the cab. This includes displays and controls for operating the train, in-cab signals, displays associated with PTC systems, the alerter, and alarms associated with equipment malfunctions;
- The need to monitor and respond to communication over the radio;
- The need to communicate with other train crew inside and outside the cab (e.g., conductor, assistant conductor); and
- The need to keep track of and conform to information provided in track bulletins (listing temporary speed restrictions; location of work zones, flag locations, constructions sites, etc.).

Engineers cite the importance of being able to rapidly prioritize among competing demands for attention, and overcoming distractions for safe operation. They indicated that managing attention demands is a difficult skill that requires experience to learn.

Engineers indicated that their first priority was running the train and responding to events outside the cab. This takes priority over other things such as responding to radio communication. For example, if they were in a situation where they were getting ready to blow the horn (e.g., at a grade crossing, saw roadway workers in the vicinity) or were getting ready to change speed, then they may delay responding to the radio.

Conversely, they indicated that if they were engaged in activity that drew their attention inside the cab, they might slow down the train to compensate. One example involved radio communication. Talking over the radio requires that engineers face the radio, therefore reducing the ability to monitor outside the cab. As a consequence, they might slow down the train a little to compensate.

Another potential source of distraction is engine malfunction alerts. The engineers stressed the need to consider tradeoffs when deciding when and how to address a nonemergency engine problem. For instance, during a head-end ride an engine developed a problem. The engineer stressed the importance of thinking through when and how to respond to the alert, so as to avoid unnecessary distraction from operating the train safely. He indicated that focusing on the engine problem could cause distraction and result in missing a speed restriction. He stressed that fixing the engine has lower priority relative to insuring that running a signal does not occur. "You don't have the luxury of not being vigilant," he commented, as lives are on the line.

Managing multiple demands on attention and knowing how to prioritize among them was mentioned as one of the greatest challenges faced by inexperienced engineers. One relatively inexperienced engineer put it this way:

> "I think for me the most difficult thing that I would do, is I'm trying to brake or get the train down to speed for either a station stop or a speed restriction and I have the dispatcher trying to communicate to me. But what I will do is for me safety first, I'll slow the train down, I'll let the dispatcher sit and wait and get back to him when I feel I'm in a safe mode. Because there is so much going on out there sometimes and safety is your number one priority. I'll just let him sit. And then, when I get on the radio with him, I'll tell him why I couldn't get back to him. I'm sure he understands. They don't yell at you or anything."

Another locomotive engineer mentioned a specific case where he was confronted with multiple competing demands for his attention. The example provides a clear illustration of the multiple simultaneous demands on attention that can arise and the need to rapidly work through the priorities among them to maintain safe operation.

> "I was brand new. I was still learning. I was pulling into a station. So, I was getting ready to stop. I was going over a grade crossing, so I was blowing the horn. Someone was calling me over the radio. It was a busy main street and there were people walking all around. When you have multitasking at that point, you have to think, 'who is the priority here?' . . . I had to worry about the road crossing first and foremost, because I don't want to hurt anyone with the train. I have to also think that I will have to stop once I get over the road crossing. I want to pull the train clear of the road crossing and then stop. Then, I can answer the radio. But I wouldn't go even near the radio until the other two things have been taken care of."

These examples provide clear indication that multiple simultaneous demands on attention represent one of the major cognitive challenges of operating a train. With experience, locomotive engineers develop the ability to rapidly prioritize among competing demands.

The results point out the importance of carefully considering the impact of changes in technology on train crew attention demands. For example, some evidence that PTC technology may require locomotive engineers to focus more of their attention on in-cab displays reducing their ability to monitor activity outside the cab (See Section 4). More research is needed to determine whether this is the case and if the need to focus attention on the PTC displays decreases with the engineers' experience.

3.2.5.3 Train Handling Strategies

Operating a train is an extremely complex task, requiring extensive knowledge of the rail line over which the train is running, and constant pre-planning of train speed and braking options several miles ahead (Booz, Allen, and Hamilton, 2006). With experience, locomotive engineers develop effective train handling strategies. Train handling strategies encompass decisions with respect to train acceleration and deceleration. The goals are to start and stop the train smoothly at the desired locations, and to control train speed so to stay within speed limits while maintaining on-time performance.

One of the main challenges relates to developing train braking strategies (Booz et al., 2006). The main elements in braking decisions relate to:

- Whether to brake in a given situation,
- The type of brake application (e.g., dynamic, air brakes, and blended),
- When to start braking, and
- The force to apply (e.g., full service or emergency).

One characteristic of train operations is that braking distances are generally long. It can take up to two miles for a coal train going at 40 mph to stop. Even at 20 mph, it can take at least half a mile. Passenger trains are lighter, but they travel at faster speeds, as a consequence their braking distances can be a mile or more.

Because braking distances are long, locomotive engineers plan ahead and anticipate the next point at which they will need to stop or operate at a reduced speed. In most cases, they will need to begin to decelerate long before they reach that location. One of the strategies that locomotive engineers developed for determining where to start braking is to identify landmarks and mile posts as cues for where to start braking.

Whereas landmarks provide a general guide as to where to start to brake, in fact, the specific location where braking needs to start and the force that needs to be applied will vary depending on a number of dynamically varying factors. These include:

- Number of cars (a freight train can have up to 200 cars),
- Total weight of the train consist,
- Mixture and distribution of loaded and empty cars (especially in the case of freight trains),
- Specific characteristics of the locomotive,
- Grade and curvature of the track (it can be hard to start on a steep upgrade and hard to slow down on a steep downgrade),
- Allowable train speed (e.g. speed restrictions),
- Weather (snow or rain), and
- Season (leaves on the track can make them slippery).

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The conditions that affect braking are constantly changing; therefore, braking decisions need to take a variety of factors into account in deciding where to start to brake and how much force to apply. One engineer explained,

> "If an engineer is at Mile Post 80, and he is required to reduce his speed at Mile Post 85, at Mile Post 80 he is already thinking about how he is going to put the brake on, where he is going to put it on, how much he is going to put it on. Let's add to that, that it is snowing, so the rails are slick, so that changes how he is going to brake, what kind of speed. The next day, the leaves are falling on the rail, so it is an additional problem."

So every day, even though he is at the same milepost, the engineer is required to think differently about the same problem.

One important input into braking decisions relates to characteristics of the particular locomotive and consist. Engineers may be assigned a different locomotive each day. As a consequence, testing out the characteristics of the brakes is important at the start of the run. In the case of passenger trains, a running brake test is required by the Federal law at the start of each run. The purpose is to determine how the train brakes are responding. This gives the engineer an idea of how that train is going to operate during the braking and acceleration process. The locomotive engineer processes that information to form expectations with respect to how the engine will respond to braking and acceleration. As one engineer stated, "He works that into his operational plan for moving that train."

In the next section, we discuss the considerations that enter into braking decisions under normal operations as well as in emergencies when a person or physical obstacle may appear on the track, or a misaligned switch may occur.

Normal Operations

Braking decisions in normal (nonemergency) operations involve a variety of considerations including a desire for a smooth ride, especially in the case of passenger trains where passenger comfort is an issue.

Locomotive engineers on passenger trains are particularly conscious of the need to maintain customer comfort. For example, one engineer mentioned the importance of not going around curves at a high speed. He indicated that he was always looking back to check if the cars were rocking.

Engineers on passenger trains described releasing the brake on the engine when coming into a station. This results in a smooth stop as well as a smooth ride when leaving the station. Other considerations in acceleration and braking decisions relate to a desire to maintain schedule, minimize wear on the brakes, and save fuel costs. For example, locomotive engineers explained that they had developed braking strategies intended to minimize the time required to complete a trip (consistent with staying within authorized speed limits). They set the brakes late to minimize unnecessary loss of speed.

Locomotive engineers also talked about strategies for negotiating track portions with varying speed limits to minimize the need to constantly accelerate and brake, which would place wear on the brakes. For example, one passenger locomotive engineer mentioned that if many curves were in a portion of track that required speed reduction to 100 mph, then he might choose to maintain a constant speed of 100 mph rather than repeatedly accelerating and braking.

Equally important are safety considerations, including minimizing the possibility for derailment. For example, freight train operators described braking strategies for stretching out a long heavy train, and insuring that cars did not bunch up, especially when going down steep grades. The concern was to avoid the possibility of derailment.

Freight operations impose more of a challenge on acceleration and braking decisions because freight trains are longer and heavier than passenger trains. A major concern relates to hilly territory where braking prematurely can make it difficult to get up the hill. It could result in stopping at an inappropriate location (e.g., a grade crossing), or could result in loss of air brakes. Similarly, potential exists for derailment if brakes are not applied appropriately.

Because freight trains can be a mile in length or more, lags occur between when the brakes are applied in the front of the train and when the cars further back begin to brake. As a consequence of when brakes are applied, cars in the back of the train will initially be running faster than cars in the front of the train. This results in train compression with cars in the middle being squeezed from both ends. Locomotive engineers need to anticipate the pulling and compressive forces within the train, particularly in hilly terrain to prevent derailments or breaking the train apart.

Emergency Situations

The focus of acceleration and braking strategies during normal operations is to maintain a smooth ride, keep to the schedule, conserve energy, minimize wear on equipment, and prevent the possibility of derailment. Another class of braking decisions arises in emergency situations where a physical obstacle or person may appear on the track or a misaligned switch or broken rail may occur.

In emergency situations the objective of the locomotive engineer is to stop or at least slow down the train, while minimizing the risk of train derailment. The engineer's actions will depend on the nature of the obstacle, the speed of the train, and the length and weight (and weight distribution) of the consist.

Braking decisions can be complex requiring rapid consideration of multiple factors. Although "rules of thumb" such as "first slow down" are often useful, experienced locomotive engineers recognize that situations can arise that require exceptions to the rule. An illustration is the case of a heat kink in the track that has the potential to cause a derailment. A locomotive engineer explained that this situation can create a dilemma. If braking quickly, the retarding force on the track structure itself might increase the chance of a derailment by further weakening the track. If braking slowly, then the train will travel over the track at a faster speed, which might result in a derailment. A solution to this dilemma that experienced locomotive engineers have implemented is to brake heavily at first (before reaching the bad portion of track) and then relax on the brake as you get closer to the bad track. This example shows that braking decisions are complex and not subject to simple rule of thumb solutions.

3.2.6 Knowledge and Memory Demands

Operating a train requires extensive knowledge and skill that is developed through training and experience. Required long-term knowledge includes operating rules and route information. In addition, train specific information and route specific information must be remembered by the engineer (e.g., temporary speed restrictions, work zones, and consist characteristics). These place additional memory demands on the engineer.

3.2.6.1 Knowledge Demands

Train crews must memorize the operating rules that apply to territory in which they are operating. Although core sets of operating rules that are common across railroads (e.g., Northeast Rules Advisory Committee or General Codes of Operating Rules) exist, typically each railroad will have their own rule books with special instructions that vary from railroad to railroad. Knowledge of the operating rules can be particularly challenging in cases of trains that operate across multiple territories that utilize different rule books. In those cases, the locomotive engineer is required to be qualified on the rule books for all the territories that they are passing through. For example, locomotive engineers that worked off of the spare board (e.g., engineers who operate in relief of other engineers) out of Albany, NY needed to be qualified on five separate rule books.

In addition, locomotive engineers need to qualify on the physical characteristics of the route. With experience, locomotive engineers develop a detailed mental model of the territory they are working. Four to 5 months may be required for an engineer to develop the knowledge to be able to think ahead and operate smoothly on a territory. The mental model needs to be highly accurate with respect to the physical characteristics of the track and surrounding territory. This includes the location and characteristics of structures and landmarks such as switches, signals, signage, bridges, stations, buildings, and grade crossings as well as the operating rules that apply to those sections of track (e.g., speed restrictions).

The knowledge and experience of a route that locomotive engineers develop over time supports anticipation and planning ahead (McLeod et al., 2005). Route knowledge allows the locomotive engineer to control the allocation of cognitive and perceptual resources based on expectations about what is upcoming. It enables locomotive engineers to detect and interpret cues in the environment more rapidly (McLeod et al., 2005).

This detailed route knowledge is critical to enable locomotive engineers to operate under low visibility conditions. It also enables them to initiate action in anticipation of upcoming conditions, such as initiating braking in anticipation of an upcoming curve or speed restriction.

3.2.6.2 Memory Demands

In addition to long-term knowledge demands, dynamically changing conditions also influence train operations, which the locomotive engineer needs to keep in mind. These impose short term memory demands. Examples are temporary speed restrictions, locations of roadway workers and work zones, and location of grade crossing with broken gates where the train needs to stop and flag to alert cars and pedestrians.

Temporary speed restrictions and work zones may be listed on train bulletins that are issued daily and reviewed before a run. In some cases, temporary speed restrictions may be issued after the train bulletin was printed, and in those cases, they will be transmitted verbally by the dispatcher over the radio.

Although in some territories signs alerting train crews to temporary speed restrictions and work zones may be seen, they are not always present or visible. They may never have been placed, signs may have been removed through vandalism, or they may be obscured by vegetation. As a consequence, locomotive engineers cannot rely on these external cues exclusively. They must develop strategies to help them remember when and where significant upcoming events such as temporary speed restrictions are expected.

One locomotive engineer said, “One of the hardest things of being an engineer are the things that you have to remember that are specific to this trip. Things like whether there are work crews out there. You can forget that. There is usually a sign but not always.” Locomotive engineers have developed a variety of recall strategies and external memory aids to help them remember significant events coming up. In addition, others within the distributed railroad system also provide proactive support to the locomotive engineers to help them remember.

Some of the memory aiding strategies included placing the train bulletin in front of them (e.g., affixing it to the front dash of the engine) and writing in the list of temporary speed restrictions in the order in which they will come up so that they can anticipate them. They would then cross them off as they passed each one so to clearly identify the next one. An locomotive engineer said, “I will probably look at it between 3 and 4 times between stops to make sure I don’t miss something.”

A related strategy involved highlighting the speed restrictions that applied to their route. An locomotive engineer explained:

> “I’ll highlight stuff. The reason why you have to is that they will give you a sheet and it can have as many as six different tracks on the sheet and you have to pick out what you are going to do. And it is fairly small print, and in a dark cab, you are paying attention to the railroad, you are listening to the radio, you are doing what you are supposed to do, those highlighted portions would be much easier to come to.”

An interesting variant of the highlighting strategy observed that was demonstrated by another locomotive engineer. He highlighted speed restrictions that definitely applied to his route with one color and those that could possibly apply (say if he was rerouted) with a different color. This strategy combines the need to focus attention on what is definitely coming up next, with the need to think ahead and be prepared to accommodate unplanned contingencies.

Locomotive engineers used sticky notes (e.g., placed on windshield) as a reminder of speed limits at different mile posts or any unusual conditions such as a unique station stop.

Similar strategies of creating external memory aids to cope with memory demands are used by new locomotive engineers to keep track of critical information such as the train schedule, which more experienced engineers eventually memorize. Several locomotive engineers indicated that when they first started they used “cheat sheets” with scheduled stops, scheduled meet points, crossings, mileposts and permanent speed restriction as memory aids, but that they have since memorized the information and no longer needed the cheat sheets.

An interesting variant was reported by one Amtrak passenger train locomotive engineer that mentioned that he created his own set of cards where he wrote down arrival and departure times for each stop. He explained:

> “That way I know if I’m on time, or I’m running fast, or I’m running slow. A lot of the trains have ‘fat time’ in them; they cushion it up, to keep their on-time schedule performance. But people get very impatient if they just sit. If you get into Providence and you have 8 minutes

> to sit there, people start wondering is there something wrong, how come we are not moving. So I may slow down a train to accommodate the fatness in the station. So I'm only sitting at the station 2 minutes vs. eight."

This is an interesting strategy that not only illustrates the use of external memory aids, but also the variety of subtle factors that enter into train speed decisions.

In addition to external memory aids, other members of the distributed railroad operations team serve to provide reminders of critical information. For example, one of the conductor's explicit responsibilities is to remind locomotive engineers of upcoming speed restrictions. Dispatchers will also sometimes call to provide reminders of upcoming speed restrictions or unusual conditions. Dispatchers are not required to provide these reminders. They do them as informal courtesies that serve to enhance the overall efficiency and safety of railroad operations.

4. Impact of New Train Control Technologies on Cognitive Demands and Operating Practice

The interviews and observations conducted at sites where new train control technologies were being introduced revealed that these new technologies can impose additional cognitive demands on train crews. These new cognitive demands, in turn, can lead to changes in how locomotive engineers operate the train. Sources of new cognitive demands include constraints imposed by the PTC braking profile that require locomotive engineers to modify train handling strategies; increases in information and alerts provided by the in-cab displays that require locomotive engineers to focus more attention on in-cab displays versus looking out the window and requirements for extensive interaction with the PTC systems (e.g., to initialize it and to acknowledge messages and alerts) that impose new sources of workload.

In this section, we summarize some of the main potential impacts of PTC systems on the cognitive demands placed on locomotive engineers and their operational consequences. These results are abstracted from a more in-depth report on the human factors impacts of the introduction of PTC systems on railroad personnel (Wreathall et al., 2007).

Two points should be noted with respect to the following results. First, the PTC systems are described and analyzed as they were implemented at the time that site visits and interviews occurred (See Table 1 for specific dates when site visits occurred). In some cases, the PTC systems have undergone substantial redesign since that time. Second, in evaluating the impact of PTC technology on locomotive engineer performance, we assumed no change in train crew configuration occurs. This was the stated operating philosophy at the time the study was conducted. The following analysis does not explicitly consider any additional sources of cognitive workload that may arise should there be a transition to single person operations.

4.1 Impact on Train Handling Strategies

A consistent finding across the systems examined (Communications-based Train Management (CBTM), advanced speed enforcement system (ASES), incremental train control system (ITCS), and Electronic Train Management System (ETMS) was that they used conservative braking profiles that required initiation of braking early to insure that train would slow down to the desired target speed under restrictive assumptions (e.g., heavy train or slippery track). This meant that under most conditions the PTC system required the train crew to initiate braking at an earlier point than they were normally accustomed.

The train crews consistently reported that they needed to learn new train handling strategies to be able to stay within the PTC braking profile. The train crews indicated that the PTC systems required that they initiate braking earlier than they were accustomed. If the locomotive engineer initiated braking later than the PTC system braking profile required, the system presented a warning (typically, first a visual warning followed, some seconds later, by an audio warning). If the locomotive engineer did not reduce speed to meet the system braking profile, then the system made a penalty brake application that caused the train to stop. A penalty brake application is highly undesirable because it significantly delays train operations and triggers documentation requirements to explain why the penalty brake occurred. As a consequence, locomotive engineers, across the systems in trial operation, consistently reported altering their braking techniques to conform to the requirements of the PTC braking profile.

Some of the locomotive engineers explained that before the introduction of the new train control system, they had developed braking strategies intended to minimize the time required to complete a trip (consistent with staying within authorized speed limits). They set the brakes late to minimize unnecessary loss of speed. This braking strategy is no longer possible with the new PTC systems.

With experience, locomotive engineers are able to develop effective strategies for staying within the braking curve of the PTC system while still operating as efficiently as possible. Locomotive engineers indicated that, as they gained experience with the PTC system, they learned to delay initiation of braking, coming as close to the point of initiating a penalty brake as possible, without actually exceeding that point to maintain efficient train operation.

One locomotive engineer provided an example of a train crew strategy for maintaining operating efficiency while avoiding a penalty brake application. The new train control system in question, ITCS, includes target speed and time to penalty (TTP) for the upcoming speed restriction (See Figure 4). The TTP starts at 30 seconds (s). When the 30-second visual warning appears, the locomotive engineer has 30 s to reduce the locomotive's speed to fall within the system specified braking curve to avoid penalty brake application. The 30-second count down continues until the locomotive engineer enters the braking curve. If the time-to-penalty brake value drops below 10 s, the system gives an audio warning. When it gets to zero, a penalty brake is initiated. If the train speed goes below the braking profile target value before the countdown reaches zero then the countdown stops. The locomotive engineer explained that if you started to slow down as soon as the 30-second countdown appeared and stabilized the value at 27 s, you would be ¾ of a mile back from the speed limit location when you slowed down. In contrast, if you stabilize it at 1 to 2 s, you will be 500 ft from it, which is more reasonable[2]. The locomotive engineer indicated that with experience, locomotive engineers tend to get closer to the edge of a penalty brake to increase train time efficiency.

[2] The specific braking values are a function of the length of train and type of braking used. In this case, the locomotive engineer was referring to 12 pound blended brake application.

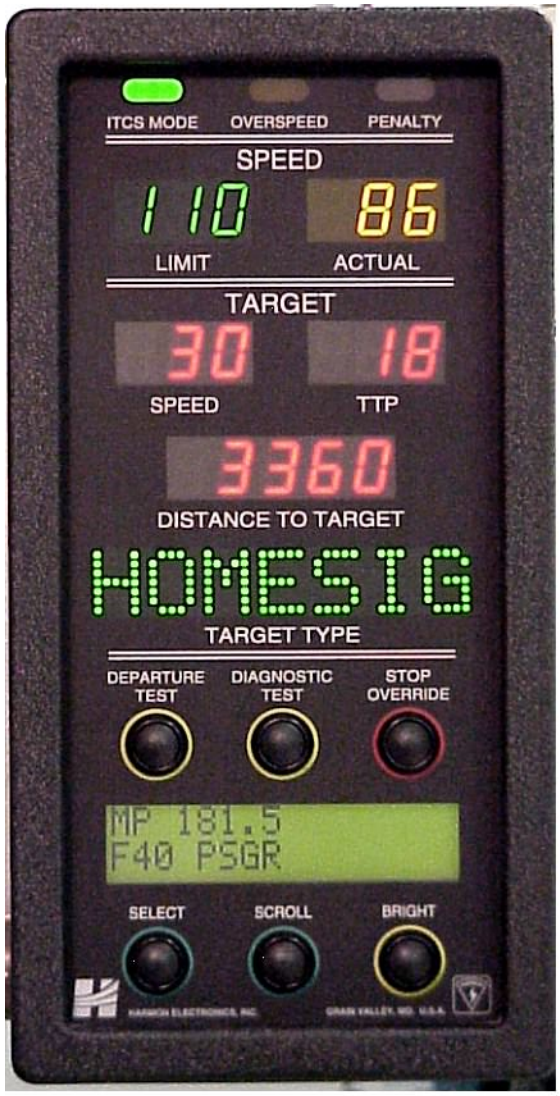

Figure 4. ITCS In-Cab Display showing current speed and speed limit, next upcoming target speed limit, the distance to target, and a count down Time To Penalty (TTP)

Locomotive engineers have also learned train handling strategies to avoid situations where the train control system might require them to stop unnecessarily. A case in point was provided by a second locomotive engineer running a train with a different train control system. The case involves approach signal updates. If the locomotive engineer comes to an approach signal, the system picks up that signal and requires the train to stop within 500 feet of the next signal—even if that next signal is green when the train reaches it (the system in question only sensed signals when it reached them; it had no indication of the reading of the signal ahead, and therefore was not able to update it's control directive). This system behavior had the potential to cause significant delays, jeopardizing the ability to meet the train schedule. With experience, locomotive engineers developed strategies to avoid these situations. They simply slowed down ahead of an approach signal until the approach signal turns to clear to avoid a situation where they enter an approach and have to stop at the next signal even if the signal is green. This is a clever strategy that, while resulting in some slowdown in train movement, is more efficient than having to come to a complete stop when it is unnecessary.

The locomotive engineers pointed out that these strategies to avoid penalty brakes, while still maintaining train running time efficiency, require significant experience to develop. They stressed that someone who was new or on the extra board would not have developed these skills. As a consequence, they would be more prone to experience significant delays and/or initiation of penalty brakes.

Interviews with locomotive engineers suggested it could take a month or more to learn where to initiate braking and adapt braking strategies appropriately. Similarly, extensive training and experience can be required to learn the variety of conditions that can arise causing the PTC to malfunction or initiate a penalty brake unnecessarily and how to avoid or deal with them. Locomotive engineers require sufficient training and experience to anticipate these situations and learn how to deal with them.

4.2 Impact on Attention Allocation and Monitoring—Shifting Attention to In-Cab Displays Versus Out the Window

Across the systems examined (CBTM, ASES, ITCS, ETMS), locomotive engineers reported a need to focus visual attention on the in-cab displays, at least initially, reducing their ability to look outside the window. Einhorn, et al. (2005) reported a similar finding. Locomotive engineers reported that they needed to carefully monitor the in-cab display to stay within the braking curve and avoid a penalty brake application while still operating at an efficient speed. The need to carefully monitor in-cab displays emerged as a particular concern in situations where there was little latitude for schedule deviation and the train needed to pass through territory with different speed restrictions. When the locomotive engineer approaches a block with a speed restriction, the locomotive engineer monitors the in-cab display carefully to stay close to the maximum possible speed, while avoiding a penalty brake. For example, in the ITCS system, engineers indicated that they carefully monitored the countdown to penalty brake readout so to avoid a penalty brake while not reducing speed prematurely (Figure 4). Locomotive engineers working with the ASES system reported using a similar strategy. In ASES, the engineers attempted to keep the current speed indicator (a black bar) close to the edge of (but still within) the green band that graphically displays the instantaneously changing maximum authorized speed that is calculated from the braking curve (Figure 5). As a consequence, when they get close to a speed restriction, the locomotive engineer focuses attention on the in-cab display and spends less time looking out the window.

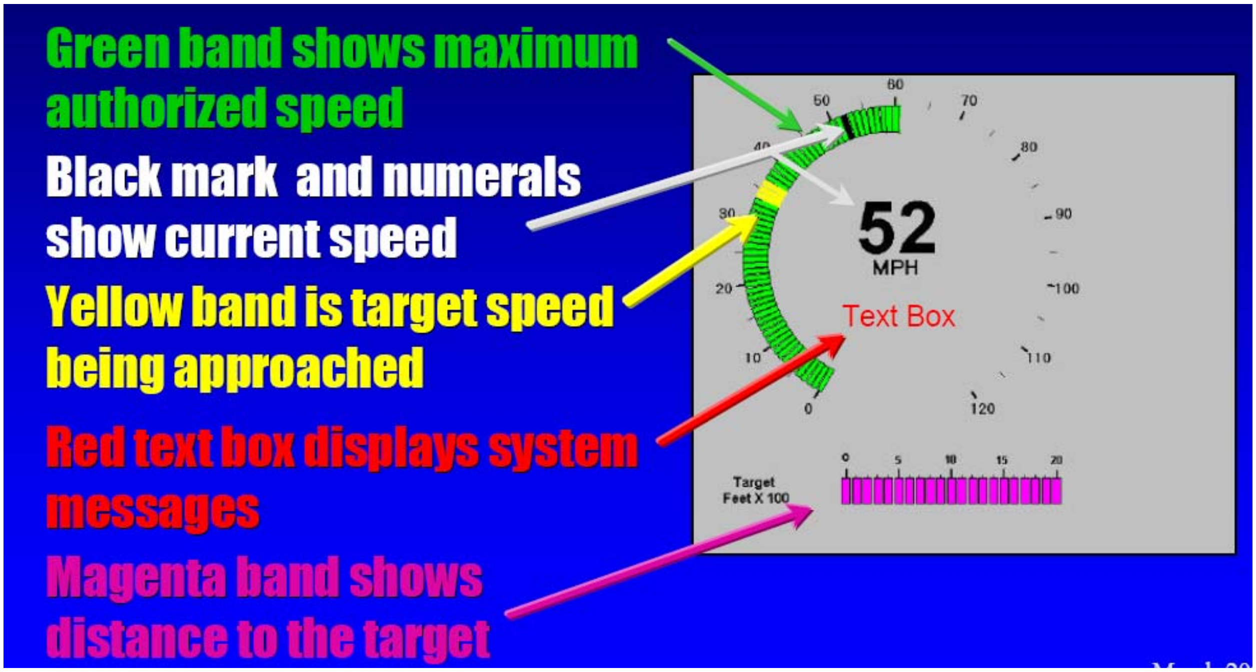

Figure 5. ASES In-Cab Display. The green band shows the maximum authorized speed, the black mark shows the current speed, and the yellow band shows the target speed being approached.

Locomotive engineers indicated that the tendency to focus attention on the in-cab PTC display, which prevented them from looking out the window, gradually lessened with experience. For example, ITCS locomotive engineers indicated that, after about a month of operating with the system, they spent less time monitoring the in-cab display. However, several of the locomotive engineers reported that, even when locomotive engineers became experienced with the PTC system, they were still not able to look out the window as much as needed.

The locomotive engineers expressed concern about situations where it is important to look out the window to avoid hitting roadway workers, pedestrians at highway-railroad grade crossings, or trespassers. For example, one locomotive engineer described traveling through a curve where people often trespass. He found himself focusing on the in-cab display to be sure he stayed within the braking curve instead of looking out the window.

The locomotive engineers indicated that they needed to maintain their focus outside the window and be prepared to sound the horn in case they see a trespasser, motor vehicle driver, or roadway worker. They were concerned that with their focus on the in-cab display, they might miss unauthorized people on the right-of-way. This issue is a particular problem in territory where many grade crossings exist.

4.3 Improved Anticipation

In addition to providing predictive braking, some PTC systems include preview information that enables locomotive engineers to anticipate and prepare for track conditions some distance ahead of the train. Information may include upcoming speed restrictions (both permanent and temporary speed restrictions), location and velocity of nearby traffic, and upcoming distance cues (e.g., mileposts, switches, and stations). Including this type of information in the PTC displays reduces memory demands on locomotive engineers (e.g., reduces the need to remember upcoming temporary speed restrictions), fosters a more accurate situation model, and makes it easier for locomotive engineers to generate expectations and prepare for upcoming conditions.

At the time we examined the PTC systems, CBTM, ASES, ITCS, ETMS and North American Joint Positive Train Control (NAJPTC) varied in the amount of preview information they provided. Comparisons will be examined of the information provided by the different PTC systems as they were implemented at the time site visits and interviews were conducted (See Table 1 for specific dates of site visits).

The CBTM system is intended as an overlay system that only activates when an authority is predicted to be violated. This system does not provide preview information. ASES shows current speed, target speed at the upcoming speed restriction and instantaneous maximum authorized speed as calculated from the braking curve.

ITCS displays current speed and target speed. ITCS also provides milepost information, giving the engineer train location. Of the systems examined, the NAJPTC system provided the most preview information. The display indicates the location, length, and current speed of the train. It also provides 6 mi of look-ahead of the track and depicts upcoming mileposts, track layout, hot boxes, sidings, and crossings.

Whereas providing upcoming track information contributes to the need for locomotive engineers to focus attention on the in-cab displays, feedback from the locomotive engineers interviewed, as well as results of simulator studies, suggests that providing the engineers with preview information is helpful. The evidence (Einhorn, et al, 2005) suggests that preview information enables engineers to make better (i.e., safer and more efficient) decisions in the time available.

Several simulator studies have demonstrated that displays incorporating preview information can increase safety and efficiency of train operation (Askey, 1995; Einhorn et al., 2005; Kuehn, 1992). Kuehn (1992) showed that displays that incorporated gradient, authority, and speed restriction preview (5 mi ahead of the train) resulted in increased safety, as measured by the number of speed violations and red signal violations, as well as reduction in fuel consumption. Askey (1995) examined the effects of providing varying levels of preview information on locomotive engineer awareness, safety, and efficiency. The study found that as levels of information display increased, performance improved on a variety of measures, including station-stopping accuracy, schedule adherence, and reaction time to unexpected signal changes. Finally, Einhorn, et al.(2005) evaluated preview displays that provided upcoming speed restrictions, location and velocity of nearby traffic, and upcoming distance cues (e.g., mileposts, switches, and stations). The study manipulated the amount of look-ahead (1.5 to 3.4 mi and variable look-ahead). The results showed that preview displays improved performance on a number of train control tasks, including routine speed control, signal adherence, brake reaction time latency and schedule adherence. Performance was best for variable preview where the amount of look-ahead varied as a function of train speed.

Interviews with locomotive engineers of PTC systems indicated that the engineers perceived preview information as valuable to improve safety and efficiency, independent of the predictive braking aspect of PTC. ITCS locomotive engineers felt that the display of milepost reinforced their mental model of the territory and provided important safety benefits in poor weather with limited visibility. Similarly, Amtrak staff interviewed regarding the NAJPTC system indicated that the NAJPTC display of the upcoming track and their location on the track would be very useful in helping them operate the train in cases where visibility was poor (e.g., in fog or at night). The preview information is expected to aid locomotive engineers in operating trains at higher speeds (e.g., above 79 mph) where there is less time available to process and respond to information outside the window.

4.4 New Sources of Workload

The PTC system creates new sources of workload and distraction. Sources of workload and distractions include the need to acknowledge frequent (and often non-informative) audio alerts generated by the PTC system and the need for extensive input to the PTC system during initialization and when error messages occur while operating the train.

4.4.1 Audio Alerts as a Source of Workload and Distraction

NAJPTC and ITCS locomotive engineers raised the issue of too many audio alerts and the need to acknowledge them as a potential workload problem.

NAJPTC locomotive engineers mentioned a specific example that occurred during a set of test runs. The PTC system includes a train location determination system (LDS) that is able to locate train position within 10 ft. However, on a couple of occasions, the LDS system experienced difficulty identifying the train location. This difficulty triggered an LDS failure alarm. The alarm beeped repeatedly and required the locomotive engineer to press a button several times to acknowledge the alarm. The operational personnel expressed concern that this resulted in a heavy workload. It required two people to handle the situation. One person acknowledged the alarms while the other continued to operate the train. This was an early test of the system, and no consequences of failing to respond to the alert occurred. In an operational system failure to respond to an alert quickly might result in a penalty brake.

ITCS locomotive engineers mentioned a similar concern with too many audio alerts that need to be acknowledged, creating unnecessary distraction and workload. One designer mentioned that, during the design process, he had removed some alerts based on recommendations of the locomotive engineers. He indicated that the system provided audio alerts to signal permission to resume speed, as well as upcoming speed restrictions. He suggested limiting alerts to warning of potential problems (e.g., an upcoming speed restriction that might be missed) and avoiding their use for positive situations (e.g., when a speed restriction is no longer in effect).

The experiences of European railroads suggest that the concern expressed by the locomotive engineers regarding too many non-informative alerts has a potential for negative safety consequences. Operators may respond to poorly designed audio alerts automatically without fully processing their meaning, thus defeating their purpose (Pasquini, et al., 2004). This is consistent with an extensive body of human factors literature that indicates that individuals are likely to ignore alarms when a high false alarm rate exists (e.g., Getty et al., 1995).

A recent analysis of signals passed at danger (SPAD) in Italian railways suggests that computerized systems intended to provide in-cab alerts of upcoming stop signals, if poorly designed, can fail to serve their intended alerting function (Pasquini, Rizzo, and Save, 2004). In the case examined by Pasquini, et al. (2004), a locomotive engineer missed a stop signal in spite of an in-cab display system that provided an auditory warning of upcoming stop signals and required an explicit acknowledgement of the alert (via a button push). The analysis conducted by Pasquini showed that, because of the way the alert system was designed, it promoted a tendency to automatically press the acknowledgement button when the alert came on without actually processing the alert message. As a consequence, even though the locomotive engineer received and acknowledged an in-cab alert indicating an upcoming stop signal, he did not know he was approaching a stop signal.

Analysis of the case reveals how poor alert system design can cause a system to lose its alerting function. One problem with the system was that the alerts were generally uninformative. The system attempted to predict the signal aspect for the next block and provide a warning, but in many cases the prediction was inaccurate. Typically, when a train entered a block (block n-1), the system would alert the locomotive engineer that the signal for the next block (block n) would be an approach signal. In most cases, the signal would turn to clear before the train reached the next block. As a consequence, experienced locomotive engineers perceived the system as a noisy distracter that must be silenced as soon as possible. Observation of train crews revealed that, as they approached a block, experienced locomotive engineers tended to look out the window with their fingers on the acknowledge button, ready to press it as soon as the auditory alert came on. They pressed the acknowledge button automatically without looking at the in-cab display that indicated whether the next signal was predicted to be approach or stop. Because the auditory sound was the same for stop and approach signal alerts, and the acknowledge button was the same in both cases, the locomotive engineers acknowledged the alert without processing whether the predicted signal aspect for the next block was a stop or approach.

This example points to several important principles for design of effective alerting systems. Most importantly, the alerts must be accurate and informative. One of the most frequent problems with alerting systems is that they have a high false alarm rate, which causes users to ignore them (Getty et. al., 1995). Second, if an audio alert is used in an environment where the user needs to look somewhere other than the display screen (in this case locomotive engineers need to look out the window), then it is advantageous to use different audio signals to correspond to different alerting conditions (e.g., a different tone for approach versus stop). Third, if users must acknowledge an alert, they are less likely to respond automatically when different actions are required for different alert messages (e.g., a different button push for approach versus stop alerts).

One of the negative consequences of alert systems with high false alarm rates is that users may disable them, particularly under heavy workload conditions. Data reported by Einhorn, et al. (in press) suggests that this is a legitimate concern with potential for negative safety consequences. The report discusses the problem of alarms as a source of workload and mentions comments made by the locomotive engineers participating in the study. One of the Amtrak engineers complained about the amount of electronic harassment in modern locomotive cabs. He related that many engineers cut out (turn off) the cab signaling and automatic train protection (ATP) in low-speed territory to remove the distraction of the warnings and focus their attention on very fine control of the train’s speed. However, the danger is that they forget to turn it on when they return to high-speed territory.

4.4.2 Initialization/Interaction with PTC as a Source of Workload

PTC systems generally require manually entered inputs at the start of a trip and after a shutdown of the system during train operations. The train crew must enter information that the system will use as parameters for safe operation. These data entry tasks provide another source of workload and distraction. In addition, manual entry errors can have safety implications.

One example relates to initialization of the PTC system at the start of a train trip. The complexity of the information to be entered varies with PTC system. The NAJPTC system provides an example of a system that involves extensive input. At the start of a trip, the train crew must enter information about the train, its consist, and what track it is on into the PTC system. Although the data to be entered is straightforward, the data entry task creates additional workload. As a consequence, operating rules must take this additional workload into account. When the authors conducted the interviews with NAJPTC operational staff, the detailed operating rules and procedures were still to be developed. The authors raised the question of initializing the PTC system when the train was stopped or running. Amtrak personnel felt that, in the case of Amtrak trains where only one person is in the locomotive cab, the train would need to be stopped.

Another example is the need to reinitialize the PTC system after it has initiated a penalty brake application. If the procedure is complex and time consuming, it may not be practical to follow. This issue arose in discussions with New Jersey Transit/ASES locomotive engineers. When a penalty brake application occurs, the locomotive engineers must cut out ASES and inform the dispatcher. They are then supposed to restart ASES. A procedure exists for cutting ASES back in, but the procedure is complex, difficult to follow, and time consuming. As a consequence, the locomotive engineers typically do not attempt to cut ASES back in. Instead, with the dispatcher's permission, they run the train without ASES operating. They are able to do this because the system is still in trial use and not required to operate the train. Once the system becomes fully operational, running a train without ASES activated may no longer be an option.

4.5 Potential for Complacency

Another concern that has been raised regarding the introduction of PTC systems is that locomotive engineers will come to rely on the PTC system to alert them of upcoming speed and authority limits and to automatically stop the train should they fail to do so themselves. The concern is that, should the system fail, the locomotive engineers will not perform as well without it as they would have, if the system had never been installed. Complacency has been used as a label to refer to this problem (Sheridan, Gamst, and Harvey, 1999). It serves as an umbrella term that combines several concerns, including concern that the train crew may not recognize that the PTC system has failed (or is off) and is no longer providing the level of support they are expecting; concern that the train crew may be delayed in detecting and responding to PTC system failures; and concern that the crew may lose skill due to lack of practice, and thus may not be able to perform tasks as well when the system is not available as they would have, had they been performing the tasks all along without aid of automation.

The term complacency comes out of the human factors literature; however, it is not a well-defined and universally accepted concept (Moray, 2000). This is partly because it has a pejorative connotation. Complacency seems to blame the person for unreasonably relying on automation and is closely related to the concepts of overreliance and excessive trust. One can define complacency as relying on automation to a greater degree than is warranted by its objective level of performance. As has been pointed out by several prominent researchers, given the many things that people must attend to at any given time, if a system is known to be highly reliable, then it is reasonable that people should come to rely on it to function properly without needing to constantly check on its performance (Moray, 2000; Sheridan, 2002). A review of studies of trust in automation suggest that, rather than being overly complacent and trusting in automation, people tend to be less trusting of the automated system's performance than is deserved by the actual reliability of the system (Moray, 2000).

In context of railroad operations, complacency refers to the potential for people to become reliant on a job aid that is intended as a back up (like PTC), such that when it fails to work (or does not work as expected), the people are more likely to fail than if the job aid had never been installed. Review of actual incidents and comments by locomotive engineers during the interviews suggest that this is a legitimate concern.

Complacency was identified as the most likely cause of one of the major rail accidents in the United Kingdom: the collision of a high-speed passenger train with a freight train on the approach to Paddington Station (London) at Southall in September 1997 (Uff, 2000). The following describes this incident and how complacency may have played a role.

Example of Event: Southall

While approaching Paddington Station on September 19, 1997, a high-speed passenger train in service from Swansea passed through a sequence of three signals, each of which indicated a need to slow and stop before an interlocking. The signal system was set for an oncoming freight train to cross in front of the high-speed passenger train (Uff, 2000). The engineer did not slow the train at any of the signals and only appeared to react when he saw the freight train crossing in front of him at a distance when it was impossible to stop. The subsequent collision occurred at a closing speed of between 80 and 100 mph and resulted in seven passenger fatalities and 139 injuries. The engineer of the high-speed passenger train survived with minimal injuries.

The HST, like most other British trains, was equipped with an automatic warning system (AWS) that warned the engineer if he was passing any signal that was more restricting than clear by sounding a warning and displaying a visual indication. By acknowledging the AWS, the engineer can continue to pass the signals; no enforcement of the signals occurs if the warning is acknowledged (and is thus not a PTC equivalent system). However, on the day of the accident, the AWS failed (and was known to be failed) in the leading cab of the high-speed passenger train as it traveled to Paddington Station.

The engineer operated the train appropriately up to the point of the accident, including obeying signals and speed limits. However, when interviewed immediately after the accident, the engineer recalled being preoccupied with getting his bag ready for arrival at Paddington Station—the terminus of the journey about 5 min from Southall. He received no warning from the failed AWS of passing the signals set to yellow and red as he approached the interlocking.

The following passage is taken from the inquiry's report:

> While drivers [engineers] accepted the traditional view that AWS was merely an "aid," the reality was somewhat different, as the Southall accident has demonstrated. While it must be emphasized that the primary duty of a driver is to keep a vigilant lookout at all times, there

> must be a tendency for drivers, to an extent, to become dependent on the security of an automatic warning system on the approach to every signal. A full understanding of the effects of such systems depends on studies of human behavior in the particular environment of the driving cab, a subject that has so far received only limited attention. It can be concluded, however, that the absence of AWS was a contributory factor to the failure of Driver ------- to respond to signals SN280 or 270 at the crucial time (Uff, 2000).

This accident, plus the SPAD accident at Ladbroke Grove involving a passenger train leaving Paddington Station in October 1999 (Cullen, 2000; HSE, 2000) led the United Kingdom rail authorities to consider the extension of train protection systems (TPS), the equivalent of PTC systems in the United States, to provide much more coverage in the United Kingdom (Uff and Cullen, 2001).

Locomotive engineers interviewed at New Jersey Transit and ITCS felt that complacency was a legitimate concern. At New Jersey Transit they mentioned an anecdotal case where a complacency effect may have contributed to missing a signal in Cab Signal territory. In the case in question, the cab signal cut out. The locomotive engineer was aware that it had cut out. However, he was momentarily distracted (talking with a supervisor) and missed a signal. The locomotive engineers stressed that the individual it happened to was known as a very careful and conscientious locomotive engineer. This anecdote reinforces the point that complacency does not reflect a lack of conscientiousness but rather a tendency to come to rely over time on highly reliable and useful systems.

4.6 Need for Awareness of Mode Transitions

Another area of concern relates to changes in modes of operation. Locomotive engineers may have difficulty transitioning back and forth between train operation with PTC and train operation without PTC. FRA initiated a study that specifically looked at the potential challenges associated with mode transitions associated with PTC systems (Wreathall et al., 2007). Here we summarize some of our own findings related to PTC mode transitions as well as the findings of the Wreathall et al. (2007) study.

Mode transitions fall into several types. One type of mode transition relates to operating a train that is equipped with PTC, but that depends on conditions and has the PTC system been active or not. PTC may not be operational on a PTC-equipped train because the train is outside of PTC territory or because the PTC system is malfunctioning. In the interviews, employees gave numerous examples of PTC-equipped trains that crossed in and out of territory where PTC coverage was available. For example, a freight train locomotive engineer operating an ITCS-equipped train mentioned that when the train went off territory (e.g., in a yard), the ITCS coverage stopped. The system did not come back on until the train returned to the main line and passed a control point. The train can travel up to 2.5 miles on the main track before the system came on. These interviews also revealed numerous situations where the PTC system became inactive because of a malfunction.

One concern with these kinds of mode transitions was that the locomotive engineer might fail to notice that the PTC system was inactive and no longer providing protection. Alternatively, the locomotive engineer may recognize that the PTC system was unavailable but fail to increase vigilance sufficiently to compensate for the lack of PTC protection. These concerns were similar to the concerns raised in the earlier section on complacency. The locomotive engineers will not perform as well when the PTC is not activated as they would have had the system never been installed because they have come to rely on it.

Interviews with locomotive engineers suggest that the possibility of failing to realize that the PTC system is no longer operational is likely to be low. Typically a prominent visual cue occurs indicating when the PTC system is operational. Locomotive engineers reported no trouble telling whether the PTC system was active or inactive. The question of whether locomotive engineers come to rely on the PTC system, and therefore perform less well when it is unavailable than they would have had it never been available is unclear. The earlier section on complacency addresses these issues.

A second, related mode-transition issue arises in the case of locomotive engineers that operate on both PTC territory and non-PTC territory. Examples include locomotive engineers working on the extra-board that might be called to operate PTC-equipped trains on PTC territory, as well as non-PTC equipped trains on a different territory. The concern is how easily the locomotive engineer can switch between the two types of operation and whether any negative transfer occurs in going from operating PTC-equipped trains to non-PTC equipped trains and vice versa.

Wreathall et al. (2007) analyzed the potential risk of human error associated with different types of PTC mode transitions. They concluded that when the PTC system is working normally, the dominant risk is the potential for human errors when the locomotive leaves the area covered by the PTC system. Contributors to errors that can arise in this case include:

- Complacency, where the train crew has become overreliant on the protection provided by PTC and forget that coverage is no longer being provided;
- Skill loss, where the train crew has lost some of the knowledge (speed limits, boundary limits, etc.) that is essential to safe handling of the train as a result of relying on the PTC system; and
- Primary/backup reversal is where the crew comes to rely on the information provided by the PTC system (such as providing current location, indications of speed limits, etc.) and therefore has more difficulty operating trains that do not have this type of information available.

Wreathall et al. (2007) indicated that risk of human error can also arise in cases where the PTC system malfunctions. They concluded that the primary concern in those cases relates to complacency following failures of the onboard equipment, where the crew, having isolated the system following its failure, forgets that coverage by the system is no longer available.

Wreathall et al. (2007) concluded that compared with the existing accident rates without PTC operations, human errors arising from work mode transitions are likely to be much lower contributors to risk of accidents. Nevertheless they argued that railroads and PTC system designers need to be made aware that new accident types are possible, and measures can be taken in the design of PTC displays and in development of user training to prepare users to avoid the potential for work mode-related accidents. Section 5 of this report outlines some of the steps that can be taken to reduce the potential for error through improvements to user interface design and training.

4.7 Impact on Teamwork Processes

Another issue to consider is the impact of the PTC system on teamwork processes among members of the train crew including the locomotive engineer and the conductor. If the display is poorly designed, or poorly located, it can interfere with the ability of team members to serve as a mechanism to catch and recover from errors. For example, in cases where two people are in the cab (e.g., a locomotive engineer and a conductor) the second individual typically is charged with serving as a redundant check/reminder to the locomotive engineer running the train. This includes calling out signals as they are seen and providing reminders of upcoming speed restrictions. If the PTC display is placed in a location so that only the locomotive engineer can see the display, it reduces the ability of the second individual in the cab to provide a redundancy check. Pasquini, et al. (2004), reviewing an Italian cab signal system, reported that the location of the cab signal interface did not allow the second locomotive engineer in the cab to read off the alert messages, thus reducing his or her ability to detect when a locomotive engineer was about to violate a signal. A similar issue was raised during the interviews with locomotive engineers and conductors regarding the CBTM system. Several of the individuals interviewed argued that it would be helpful to place CBTM displays on the conductor's side, as well as the side of the locomotive engineer so that the conductor could better support the locomotive engineer.

5. Implications for Introduction of New Train Control Technology

Section 4 revealed that the introduction of new technologies, particularly PTC technology, has resulted in changes in the cognitive demands associated with operating a train. Some cognitive demands, such as the memory demands associated with keeping track of dynamically changing temporary speed restrictions, have been reduced. At the same time new demands have emerged such as the need to monitor in-cab PTC displays with the consequence that the ability to monitor outside the window for unanticipated situations have been reduced. Although PTC technology is likely to have a positive impact on overall risk of accidents, these new sources of cognitive demand can contribute to errors and accidents (Wreathall et al., 2007). Railroads and PTC system designers need to be made aware that measures can be taken in the design of PTC displays and in development of user training to improve train crew performance and reduce the potential for human error. Some of the steps that can be taken to improve PTC user interface design and train crew training are discussed.

As noted in Section 4, the analysis provided in this report assumes no change in train crew configuration. This was the stated operating philosophy at the time the study was performed. Additional sources of cognitive workload may arise should there be a transition to single person operations that will need to be explicitly examined.

5.1 Design Implications

Current PTC displays vary widely in the amount of preview information they provide. More guidance is needed on the contribution of preview information on safety. Evidence from simulator research suggests that preview information may have a beneficial effect on safety independent of the predictive braking aspect of PTC. More research is needed to explore the relative risks and safety benefits associated with preview information displays (that may divert attention from out the window) and to develop guidelines for the design of displays that provide valuable preview information without excessively diverting attention from out the window.

The fact that locomotive engineers will attempt to operate the trains to minimize running time while staying within the bounds of the PTC braking curve has implications for design of the in-cab displays. The in-cab displays currently provide limited cues with respect to when to initiate braking so as to stay within the braking curve. If the locomotive engineers initiate braking to avoid warning messages, they are likely to brake too soon leading to unnecessary time delays. A substantial learning curve exists to develop efficient braking strategies while avoiding a penalty brake application. In addition, the strategies that the locomotive engineers have developed require closely monitoring the in-cab display. A need exists for development of in-cab displays that make it easier to anticipate and stay within the braking curve without having to look closely at the in-cab display so that more attention can be allocated to looking outside the window.

The locomotive engineers argued for the importance of being given the authority to suppress a penalty brake under conditions where it is inappropriate and potentially a safety hazard. It is important to put in place mechanisms to allow the locomotive engineer to override the automation and supporting operating rules that specify the conditions under which the engineer may do so. Situations will inevitably occur that are different than what the system designers anticipated and planned for. Providing some discretion to the locomotive engineer on the scene is important to deal with these unanticipated situations.

A valuable area for research and development is improved in-cab displays that minimize the need to visually attend to the in-cab display to extract important information. Developing alternative display approaches would be desirable for indicating to the locomotive engineer where train speed is in relation to the desired deceleration rate without having to closely monitor the visual in-cab display. Options to explore include the use of nonvisual display modes, such as auditory or tactile displays (Sklar and Sarter, 1999). Heads-up displays that would allow the engineer to track critical operating parameters while still looking out the cab may provide an alternative promising research direction.

5.2 Training Implications

Introduction of PTC systems impose new training requirements for locomotive engineers. First, training is needed to understand how the PTC system works (technical theory). Second, training is needed to understand how to operate the PTC system under different conditions (e.g., how to initialize it, what the different PTC displays mean, what error modes might arise, and what to do in those different conditions) and the applicable operating rules (PTC operations). Third, hands-on experience is required to reduce the attentional demands associated with monitoring in-cab displays. Interviews with locomotive engineers suggest that a substantial learning curve exists to reach the point where the in-cab display does not serve as a source of distraction, diverting attention away from events out the window. Locomotive engineers must have sufficient experience in running a PTC-equipped train as part of training so that they get beyond the point where close monitoring of the in-cab display is required to avoid a penalty brake application. Fourth, hands-on experience and/or simulator training is required to learn the new train handling and braking strategies required to operate a PTC-equipped train to run efficiently while staying within the PTC braking profile (hands-on train handling). Finally, hands-on experience is needed to learn how to handle the traps, challenging situations, and failure conditions that are known to arise in special circumstances.

Interviews with ITCS and ASES locomotive engineers indicated that current training typically involves a combination of classroom instruction on how the PTC system works followed by several trips with an experienced engineer. The interviews showed that the classroom training gave the engineers a solid foundation on how the equipment worked but that more hands-on experience was needed in running a PTC-equipped train.

Several locomotive engineers indicated that one of the limitations of current training is that it does not provide sufficient opportunity to develop the new train handling and braking skills required to operate a PTC-equipped train. It also does not provide sufficient experience with non-routine situations (e.g., different malfunctions) and how to deal with them. One of the locomotive engineers suggested providing an opportunity for trainees to operate a PTC-equipped train in a more controlled environment (e.g., run a test train or a train simulator) where they would be able to practice train-handling skills without concern of the consequences of inadvertently initiating a penalty brake. Another advantage of running in a controlled environment, such as a test train, is that it would be possible to simulate different types of rare conditions that can arise so the trainee could learn what displays would come up (e.g., what error codes appear) and how to handle the situation.

Examples of the kinds of special conditions that can arise and require specialized strategies include cases such as traveling on a steep uphill grade with a fully loaded train and coming upon a PTC enforcement target location; and operating a PTC train with inaccurate consist information.

Another issue raised with respect to training is the need to train crews to run the trains without the PTC system on, so that if the system ever fails, the engineer will still be able to operate the train safely. Locomotive engineers might become dependent on the PTC system to the point where they would not be able to run the train safely without it.

It may be possible to selectively turn off some of the features of the PTC in-cab display to provide practice in running the train without them. For example, one of the lead engineers of the NAJPTC display suggested that some of the PTC interface features, such as the 6-mile track look-ahead display on the bottom of the screen, could be selectively turned off. Although the track look-ahead is likely to be a very useful feature for supporting situation awareness of the locomotive engineer, especially when outside visibility is low (e.g., in fog or at night), it may be useful to turn it off during some portion of training to insure that the train crews develop their own mental models of the track so that they are able to operate safely in cases where the PTC system is unavailable. Train crews may want to operate with the PTC system inactivated for selected trips during revenue service to maintain their territory knowledge as well.

References

Askey, S. (1995). Design and Evaluation of Decision Aids for Control of High-speed Trains: Experiments and Model. Cambridge MA: The MIT Press

Bisantz, A. and Roth, E. (in press). Analysis of Cognitive Work. In Deborah A. Boehm-Davis (Ed.) *Reviews of Human Factors and Ergonomics Volume 3.* Santa Monica, CA: Human Factors and Ergonomics Society.

Booz, Allen, and Hamilton. (2006). ECP Brake System for Freight Service - Preliminary Report. Washington, DC: Federal Railroad Administration. http://www.fra.dot.gov/downloads/safety/ecp_report_20060811.pdf

Crandall, B., Klein, G.A., and Hoffman, R.R. (2006). Working Minds: A Practitioner's Guide to Cognitive Task Analysis. Cambridge, MA: The MIT Press.

Cullen, W.D. (2000). The Ladbroke Grove Rail Inquiry. Norwich, UK: HSE Books.

Einhorn, J., Sheridan, T.B., and Multer, J. (2005). Preview information in cab displays for high-speed locomotives. Washington, DC: Department of Transportation, FRA. http://www.fra.dot.gov/downloads/RRDev/ord0412.pdf

Getty, D.J., Swets, J.A., Pickett, R.M. and Gonthier, D. (1995). System operator response to warnings of danger: A laboratory investigation of the effects of the predictive value of a warning on human response time. *Journal of Experimental Psychology: Applied*. 1(1), 19 – 33.Gillis, I. (2005). Cognitive Workload of Train Drivers. Ehsal, European University College, Brussels, Belgium.

Hamilton, W.I., and Clarke, T. (2005). Driver performance modelling and its practical application to railway safety. Applied Ergonomics, 36, 661–670.

Hollnagel, E., Woods, D., and Leveson, N. (Eds.). (2006). Resilience engineering: concepts and precepts Aldershot, UK: Ashgate.

HSE. (2000). The Train Collision at Ladbroke Grove 5 October, 1999. Norwich, UK: HSE.

Jansson, A., Olsson, E., and Erlandsson, M. (2006). Bridging the gap between analysis and design: improving existing driver interfaces with tools from the framework of cognitive work analysis. Cognition Technology and Work, 8, 41–49.

Klein, G.A., Ross, K.G., Moon, B.M., Klein, D.E., Hoffman, R.R., and Hollnagel, E. (2003). Macrocognition. IEEE Intelligent Systems (May/June 2003), 81–84.

Kuehn, G. (1992). Advanced Train Control System Evaluation: Final Report. Washington, DC: U. S. Department of Transportation, Federal Railroad Administration. FRA/ORD-92/32

Luke, T., Brook-Carter, N., Parkes, A.M., Grimes, E., and Mills, A. (2006). An investigation of train driver visual strategies. Cognition Technology and Work, 8(1), 15–29.

McLeod, R.W., Walker, G.H., and Moray, N. (2005). Analysing and modelling train driver performance. Applied Ergonomics, 36, 671–680.

Moray, N. (2000). Are observers ever really complacent when monitoring automated systems? In Proceedings of the IAE 2000/HFES 2000 Congress. Santa Monica, CA: Human Factors and Ergonomics Society.

Pasquini, A., Rizzo, A., and Save, L. (2004). A methodology for the analysis of SPAD. Safety Science, 42(5), 437- 455.

Potter, S. S., Roth, E. M., Woods, D., and Elm, W. C. (2000). Bootstrapping multiple converging cognitive task analysis techniques for system design. In J. M. Schraagen, S. F. Chipman & V. L. Shalin (Eds.), Cognitive Task Analysis. Mahwah, NJ: Erlbaum.

Roth, E. M., Malsch, N., and Multer, J. (2001). Understanding how train dispatchers manage and control trains: Results of a cognitive task analysis. Washington, D C: U. S. Department of Transportation/Federal Railroad Administration. (DOT/FRA/ORD-01/02) Available online at: http://www.fra.dot.gov/downloads/Research/ord0102.pdf

Roth, E. M., Multer, J., & Raslear, T. (2006). Shared situation awareness as a contributor to high reliability performance in railroad operations. Organization Studies, 27(7), 967 - 987.

Schraagen, J. M., Chipman, S. F., & Shalin, V. L. (Eds.). (2000). Cognitive Task Analysis. Mahwah, NJ: Lawrence Erlbaum Associates.

Sheridan, T. B. (2002). Humans and Automation: System Design and Research Issues. Santa Monica, CA: John Wiley & Sons, Inc. in cooperation with the Human Factors and Ergonomics Society.

Sheridan, T. B., Gamst, F. C., & Harvey, R. A. (1999). Reliance and Distraction Effects in PTC Automation. Cambridge, MA: John A. Volpe National Transportation Systems Center. http://www.fra.dot.gov/downloads/research/reliance.pdf.

Sklar, A. E., & Sarter, N. B. (1999). Good Vibrations: The use of tactile feedback in support of mode awareness on advanced technology aircraft. Human Factors 41(4), 543 - 552.

Uff, J. (2000). The Southall Railroad Accident Inquiry Report. Norwich, UK: HSE Books.

Uff, J., & Cullen, W. D. (2001). The Joint Inquiry into Train Protections Systems. Norwich, UK: HSE Books.

Wreathall, J., Roth, E., Bley, D. and Multer, J. (2007). Human factors considerations in the evaluation of processor-based signal and train control systems. Washington, DC: U. S. Department of Transportation/Federal Railroad Administration. DOT/FRA/ORD-07/07. http://www.fra.dot.gov/downloads/Research/ord0707.pdf.

Wreathall, J., Woods, D. D., Bing, A. J. and Christoffersen, K. (2007). Relative risk of workload transitions in positive train control. Washington, D C: U. S. Department of Transportation/Federal Railroad Administration. DOT/FRA/ORD-07/12. http://www.fra.dot.gov/downloads/Research/ord0712.pdf.